IPP-Kolloquium, Dezember 2001

First island divertor experiments on the W7-AS stellarator

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Outline:

1. **Motivation**
2. **Island divertor characteristics**
3. **Divertor geometry in W7-AS**
4. **Major aims of the programme**
5. **Plasma performance at high density**
6. **Divertor regimes**
7. **Operational ranges**
8. **Summary**

Motivation

- ***Stellarators will need divertors*** **for plasma exhaust.**

- **Solutions have to be compatible with stellarator configurations.**

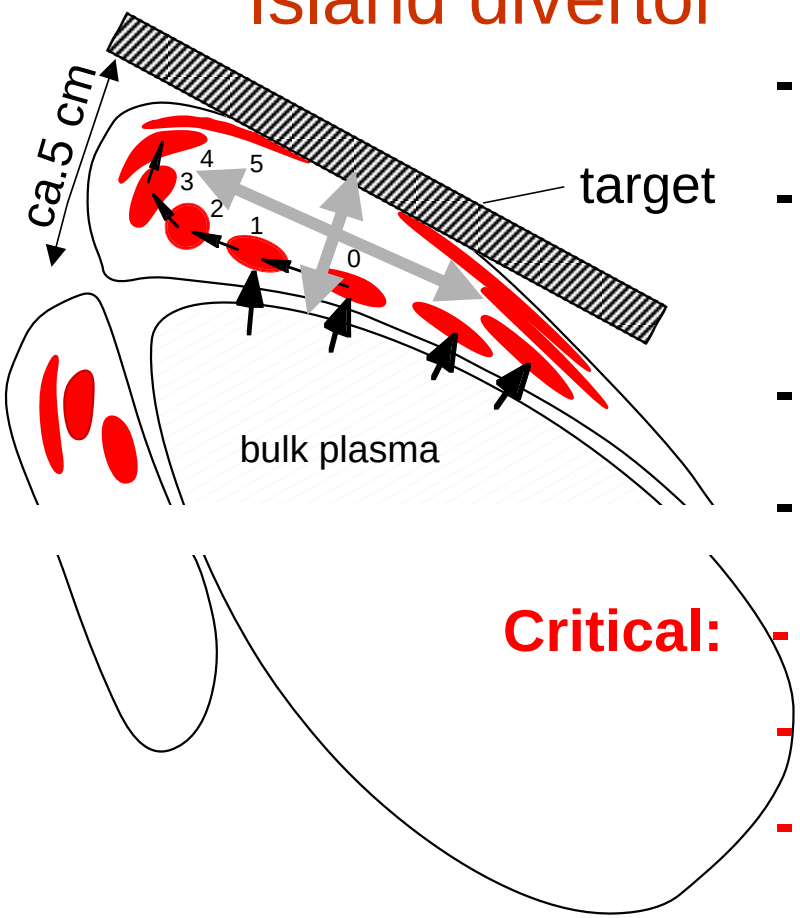
- **Utilize flux diversion by magnetic islands at the edge**
  ----> *Island divertor*

- **W7-X: study of the reactor potential of this concept.**

- **W7-AS can be operated with similar edge structure, divertor studies provide preparatory information.**

Major studies have been started in March 2001

Island divertor characteristics



- 3D SOL
- toroidally discontinuous targets
- 2D deposition zones on targets
- long field line connection lengths (small pitch)
- short distance main plasma - target
- flux compression

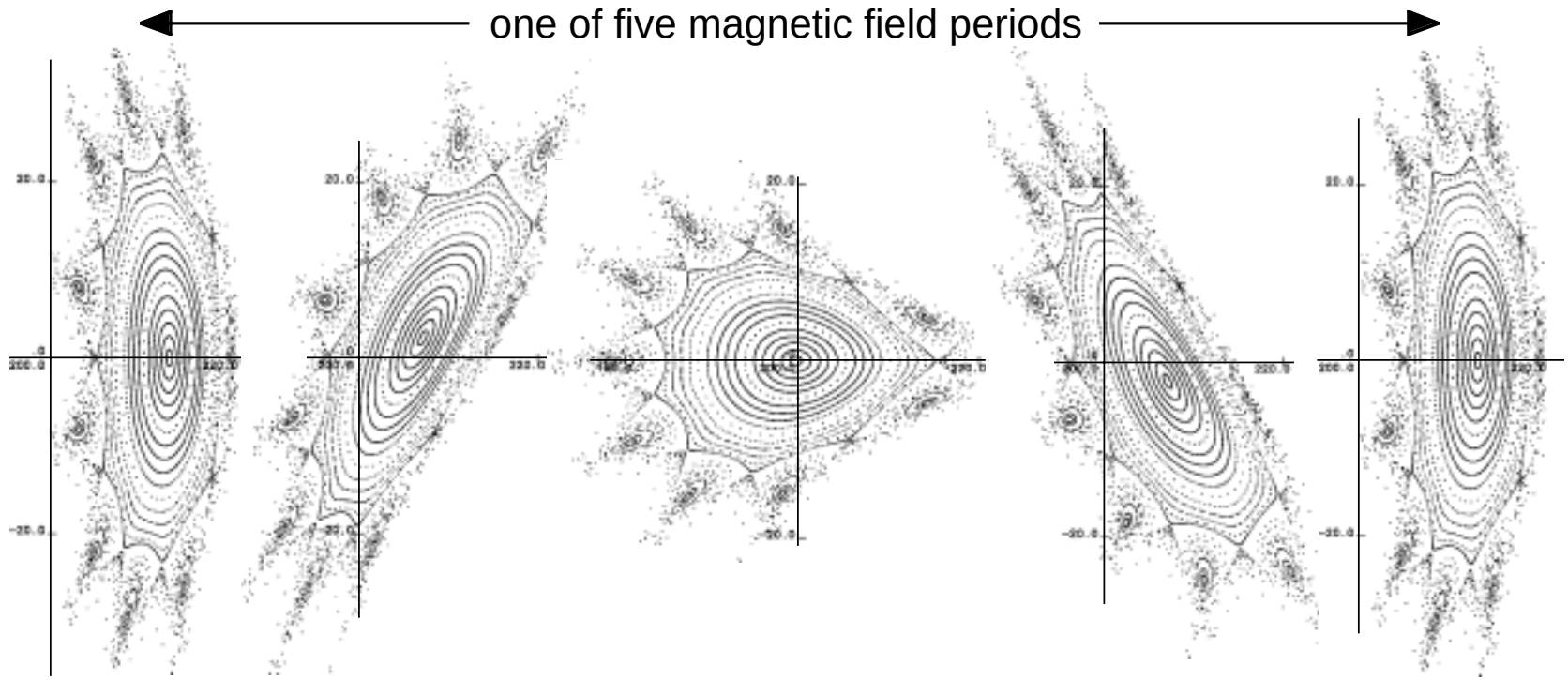
Critical:

- cross field transport
- penetration of recycling neutrals
- baffling

Divertor geometry in 7-AS: boundary islands

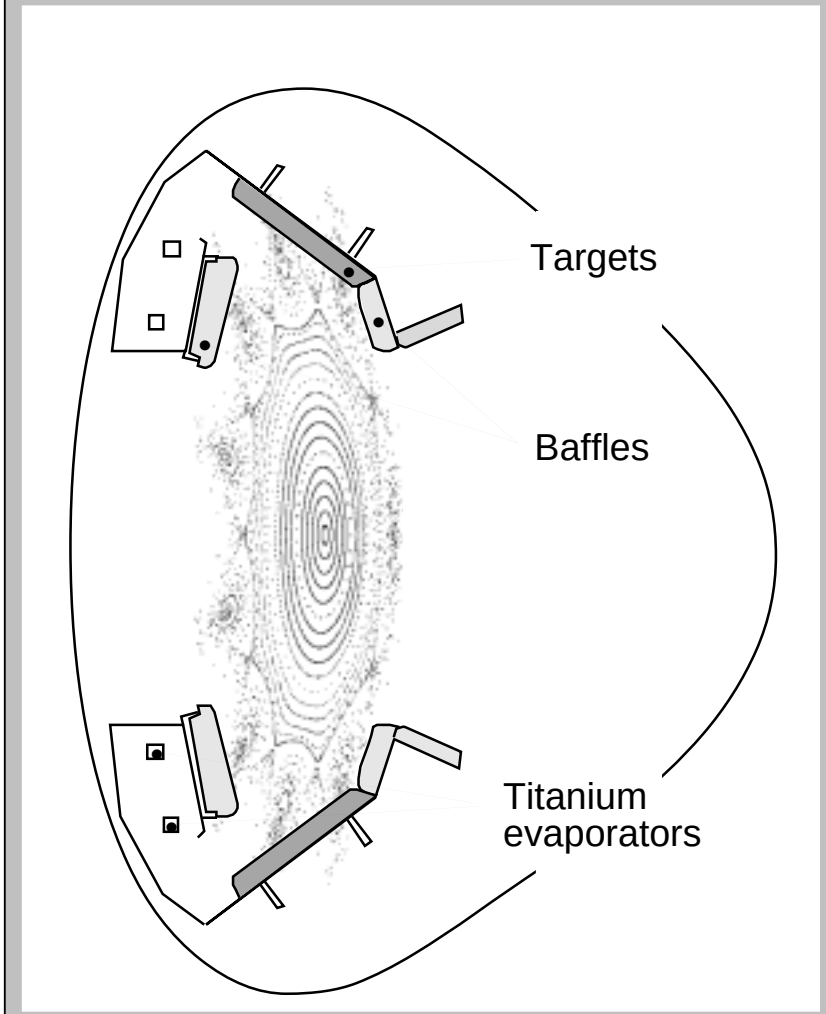
R **= 2 m, *a* ≤ 0.16 m, *B* ≤ 2.5 T, non-planar coils, five field periods**

- **can be operated with large magnetic islands at the edge**
- **rad. position can be varied by adjusting the rot. transform**
- **rad. width can be varied by special control coils**

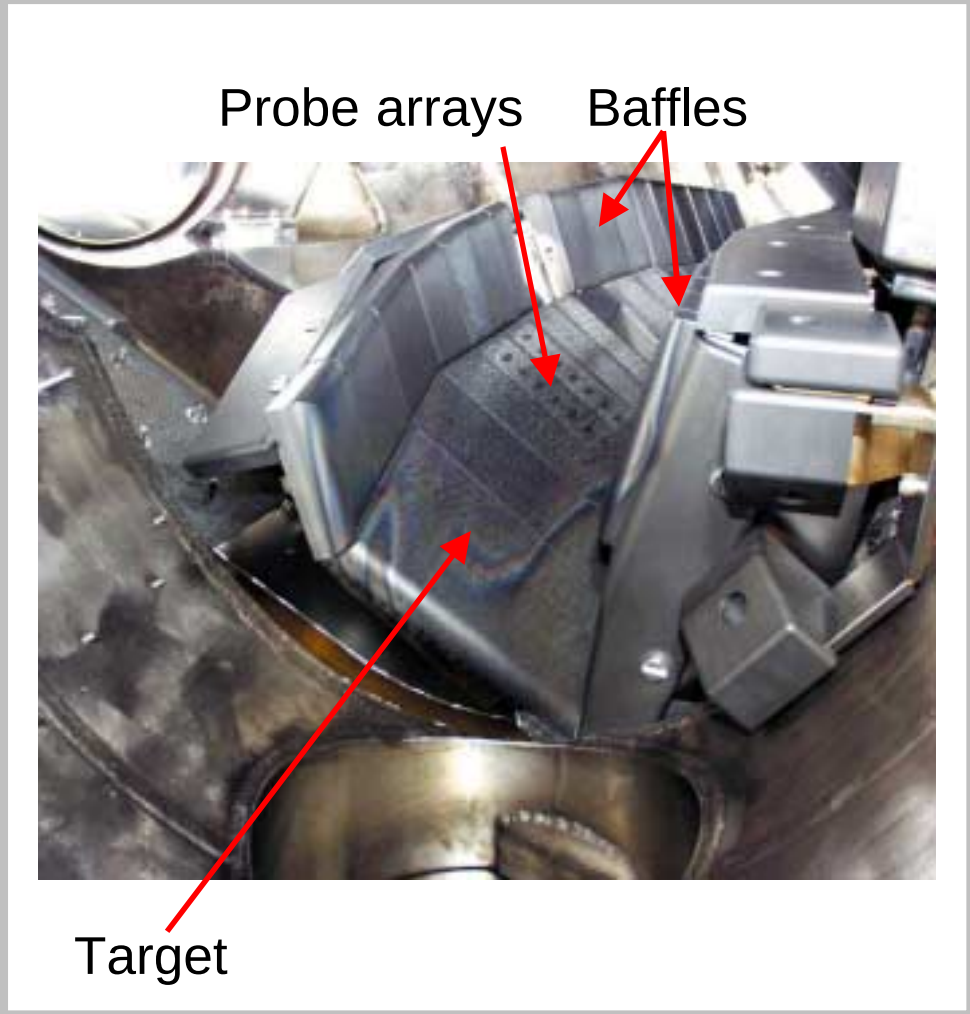


Divertor geometry in W7-AS

Ten divertor modules



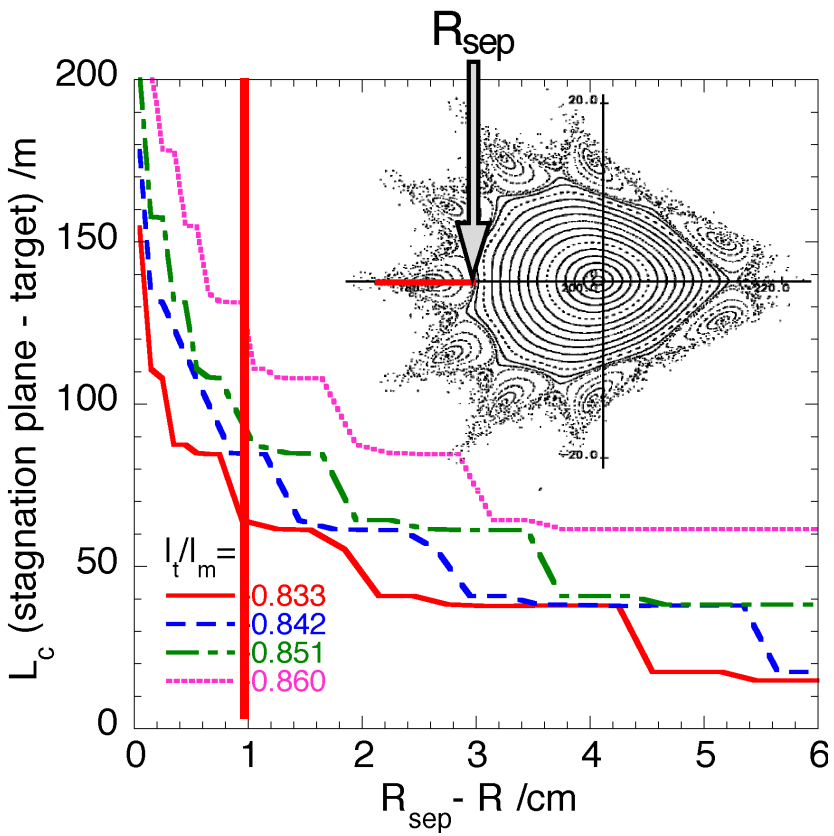
Bottom divertor

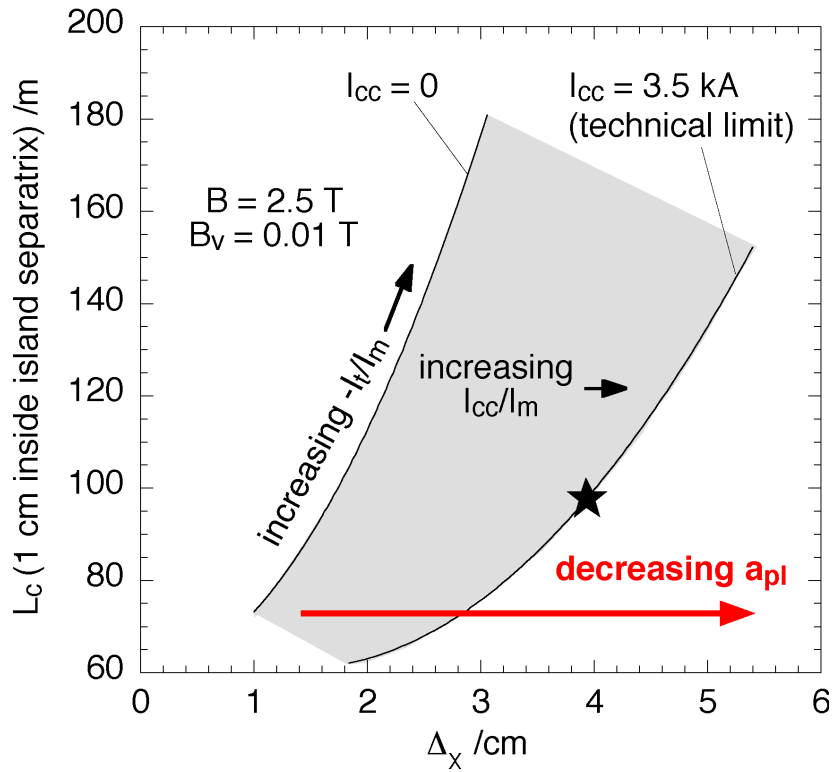


Divertor geometry in W7-AS: topological parameters

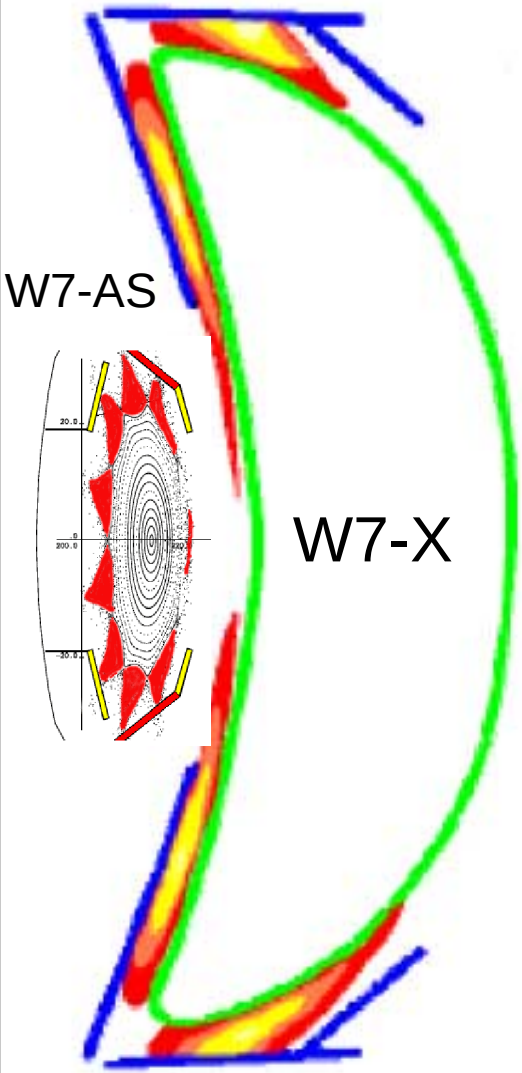
Field line connection lengths L_c decrease with increasing distance from main plasma.

L_c and distance Δ_x between x-points and targets can be independently varied.





Divertor geometry in W7-AS: W7-AS versus W7-X



Differences:

	W7-X	W7-AS
Major radius	5.5 m	2.0 m
Minor radius	0.5 m	0.16 m
Rot. transform (edge)	5/6, 5/5, 5/4	5/9 (5/8)
Island poloidal width	0.5 m	0.05 m
Toroidal length of divertor	5 m	0.7 m
Pumping capability	Cryo-panels	Ti-gettering

Similarities:

Magnetic shear (edge)	$\Delta\iota/\Delta r = 0.75\ m^{-1}$	$\Delta\iota/\Delta r = 0.5\ m^{-1}$
Island radial width	0.1 m	0.1 m
Fieldline connection length	100 m	100 m
X-point distance to target	4 cm	4 cm

Major aims of the programme

To answer the questions:

- ***Effects of the new divertors on the plasma performance?***

- ***Cold divertor plasmas without too strong cooling of the core ?***

- ***Controlled? Compatible with active particle pumping?***

- ***Compatible with improved confinement scenarios (e.g. ELMy H-mode)?***

Data shall be used to validate the EMC3-EIRENE code.

Previous operation with inboard limiters

High power NBI:

- maximum $\bar{n}_e \approx 2.5\ 10^{20}\ m^{-3}$ (depending on power)
- no density control,
- impurity accumulation, $\tau_{imp} \propto n_e(0)/P^{0.8}$,

  --> transient discharges,
- extremely low edge densities, $n_{es}/\bar{n}_e \approx 0.1$,
- high edge density sufficient for divertor operation

  only transiently achieved (strong gas puff).

Summary of main results

Access to a new regime with NBI at very high density (up to $\bar{n}_e \approx 4 \times 10^{20}$ m^{-3}) with improved confinement:

- **τ_E steeply increases with density,**
- **τ_p and τ_{imp} decrease with increasing density ($\tau_{imp} \approx \tau_E$ at highest density)**

→ **Density control already without Ti-gettering,**

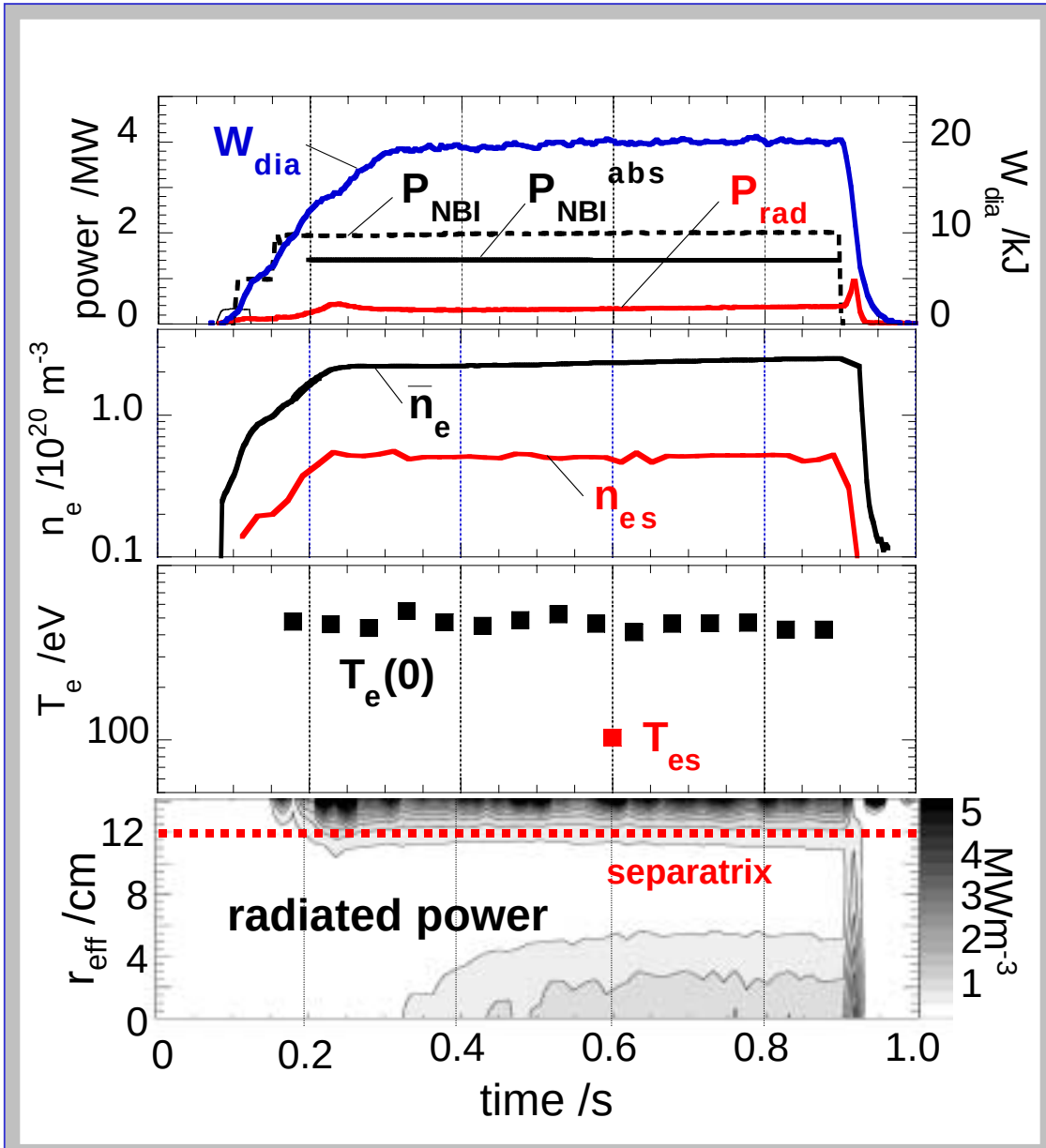
→ **quasi-steady state operation also including partial detachment,**

→ **radiatiation always peaked at the edge.**

Record value of <ß> = 3.1% achieved (at B = 0.9 T)

Plasma heating by HF (EBW 140 GHz) successfully demonstrated.

Plasma performance at high density: access to stationarity



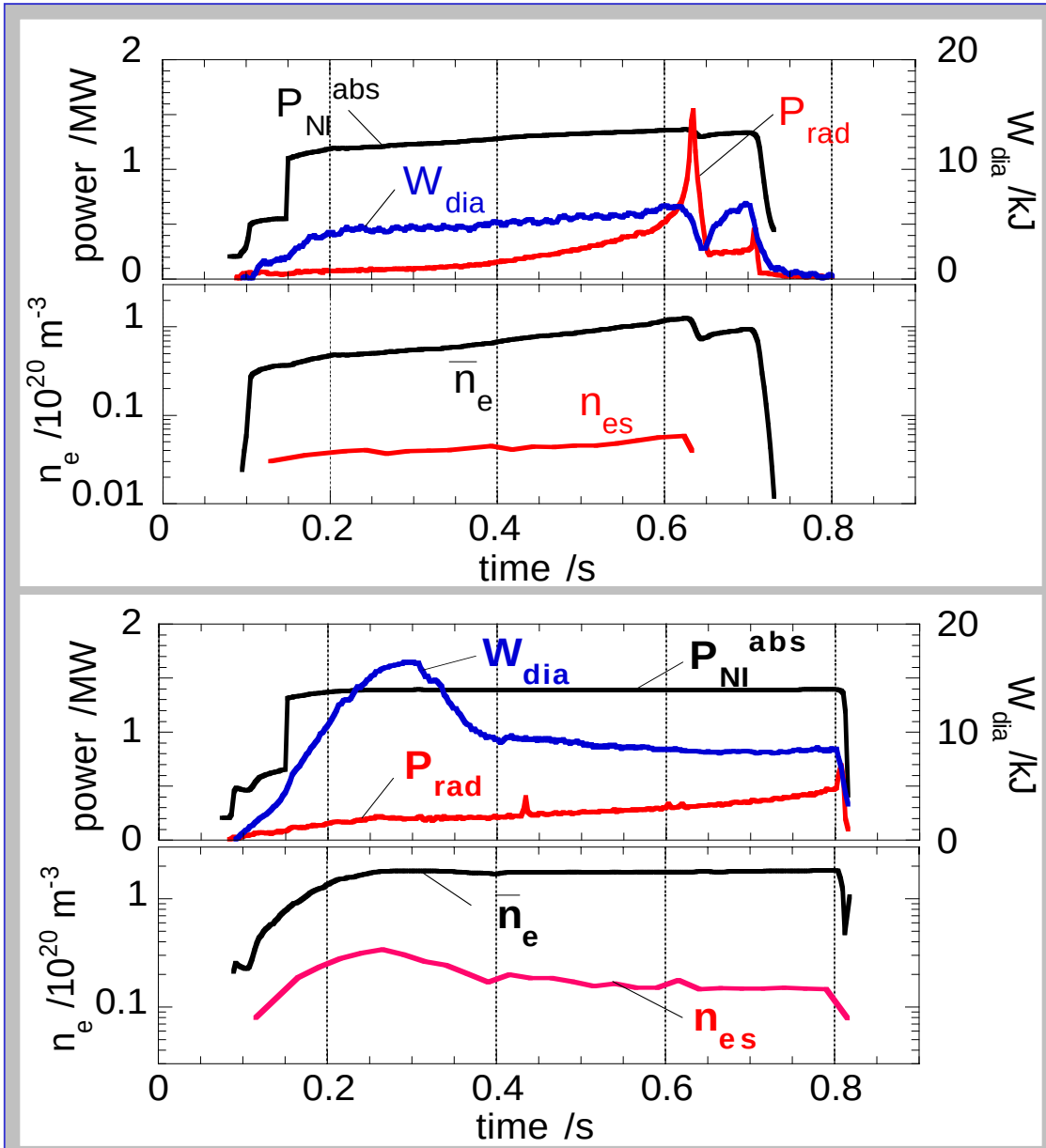
$\bar{n}_e$ = 2.5 10^{20} m^{-3}

improved confinement (IC)

quasi steady-state

- stored energy ≈ 20 kJ
- $T_e(0)$ ≈ 500 eV, ν^* ≈ 0.3
- edge density ≈ 5 10^{19} m^{-3}
- edge temperature ≈100 eV
- radiation edge-dominated

Plasma performance at high density: trans. to stationarity



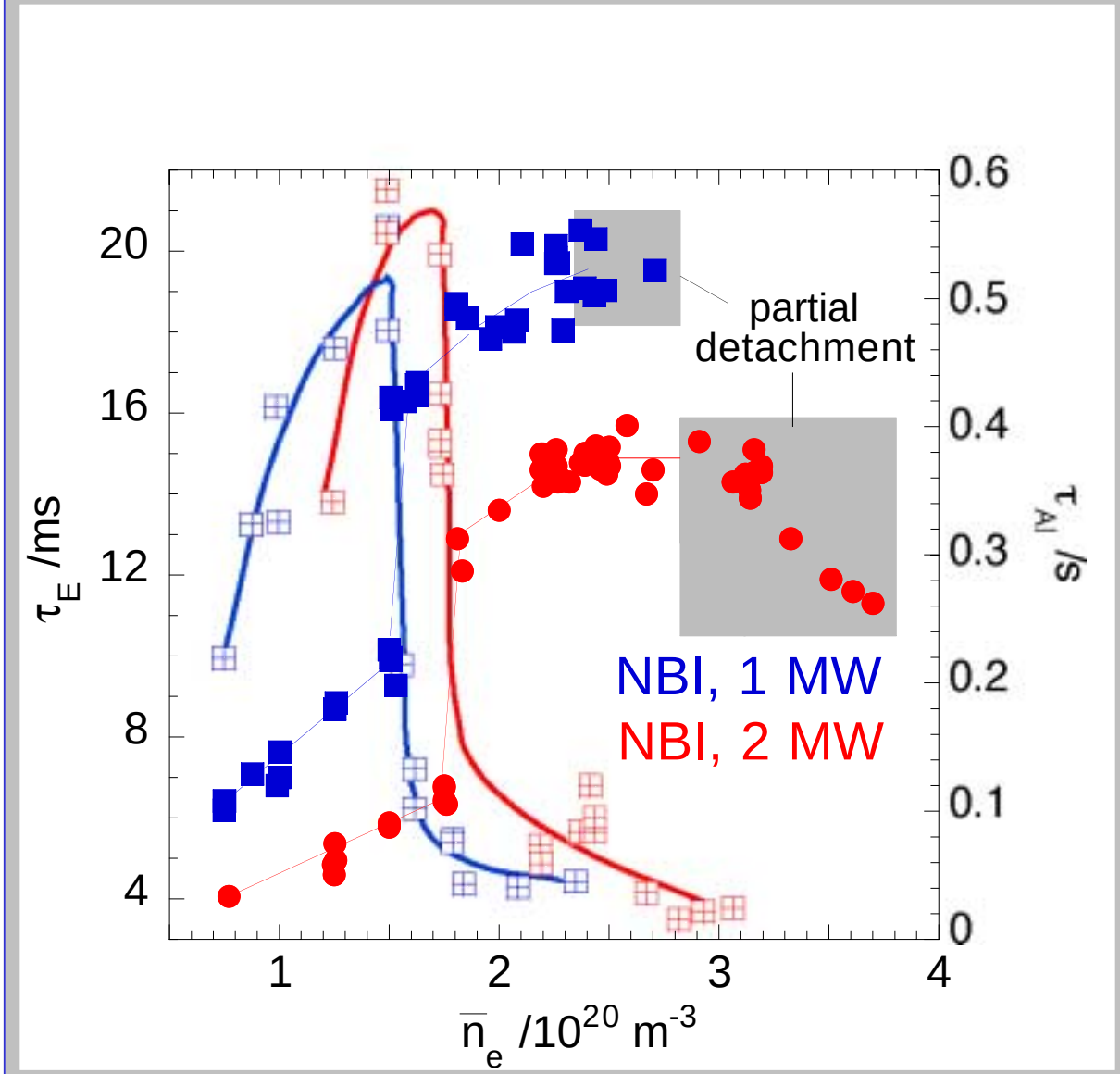
$\bar{n}_e < 1.8\ 10^{20}$ m^{-3}

normal confinement (NC)

unstationary

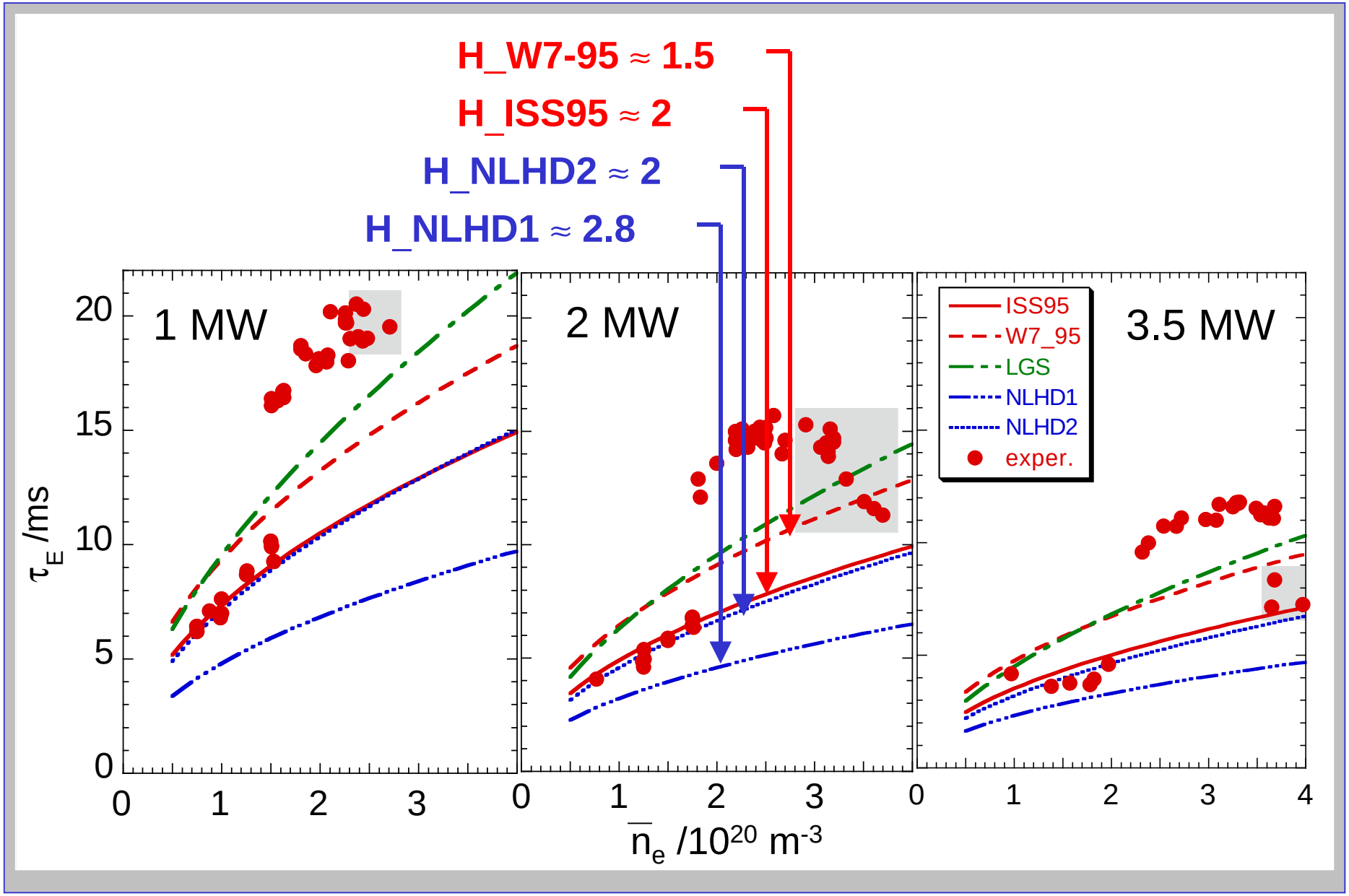
- **stored energy < 10 kJ,**
- **radiation increasing with time,**
- **extremely small edge density**

Plasma performance at high density: improved confinement



- **IC: steep increase (´jump´) of τ_E,**
- **low to moderate τ_E degradation at partial detachment**
- **steep drop of τ_{imp}**

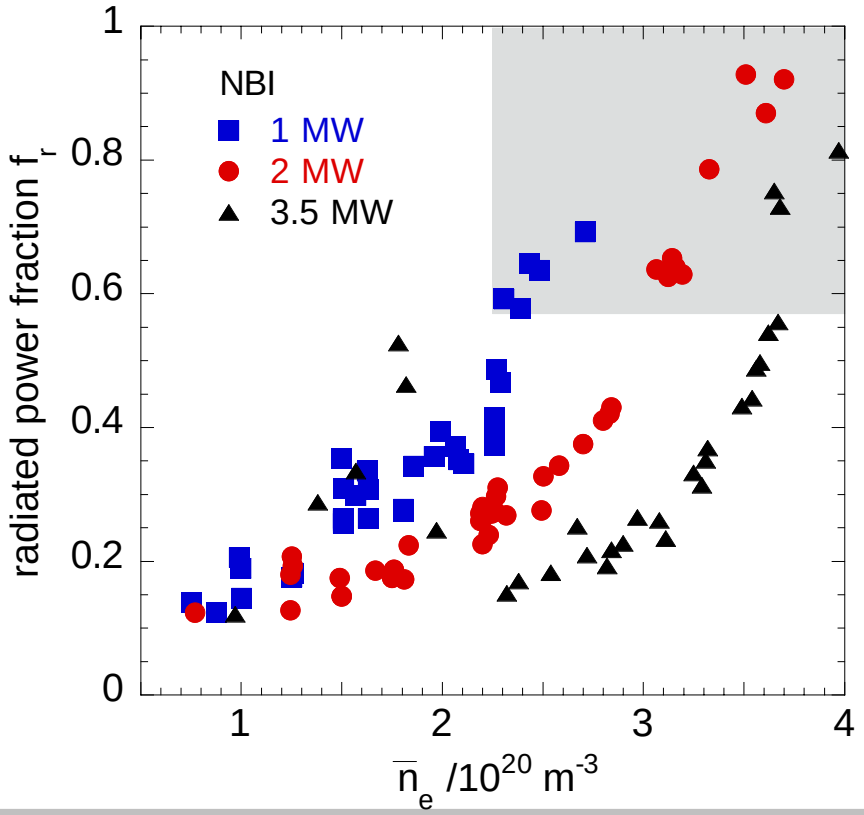
Plasma performance at high density: improved confinement

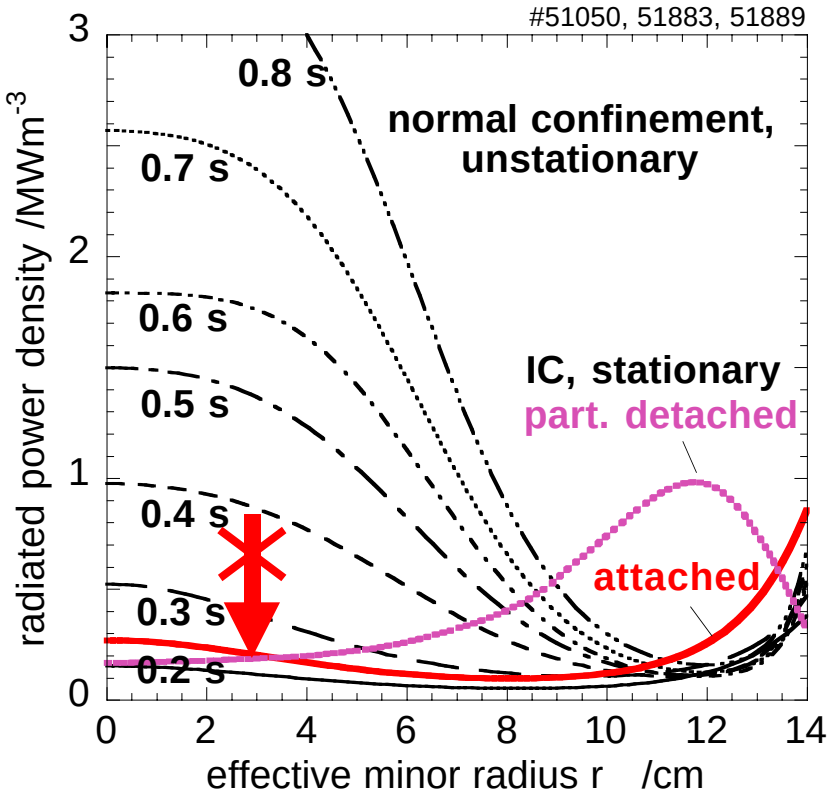


Plasma performance at high density: plasma radiation

- **radiated power fraction low to moderate in attached regimes,**
- **up to 90% at detachment**

- **NC: core-dominated radiation, unstationary**
- **IC: edge-dominated radiation, stationary**

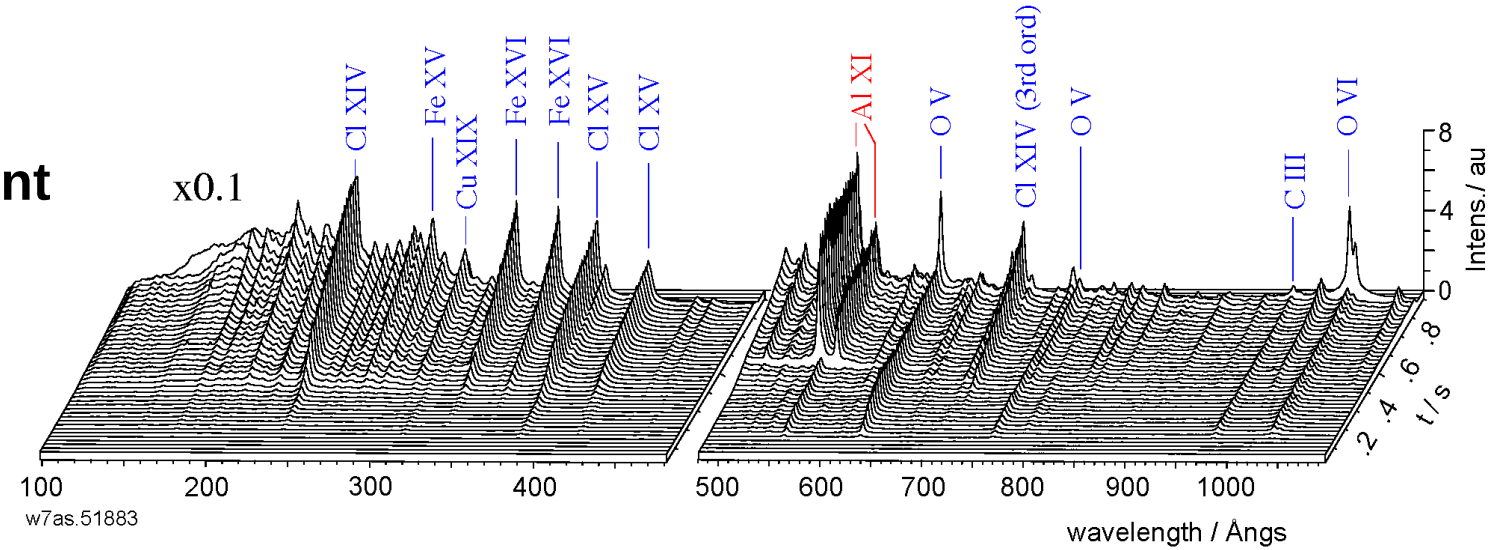




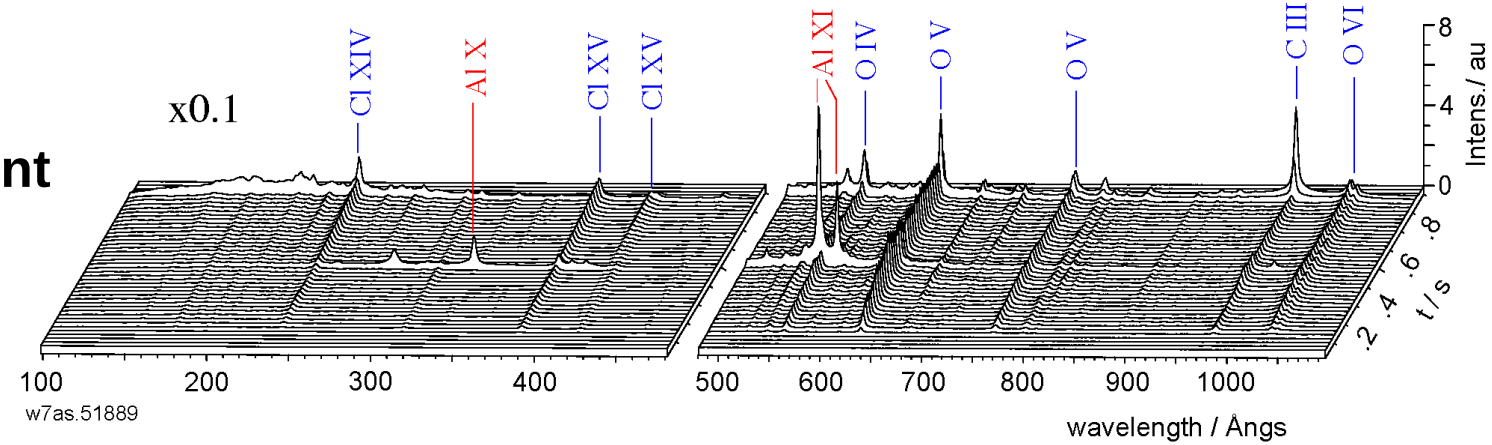
Plasma performance at high density: plasma radiation

SPRED overview spectrometer:

Normal confinement

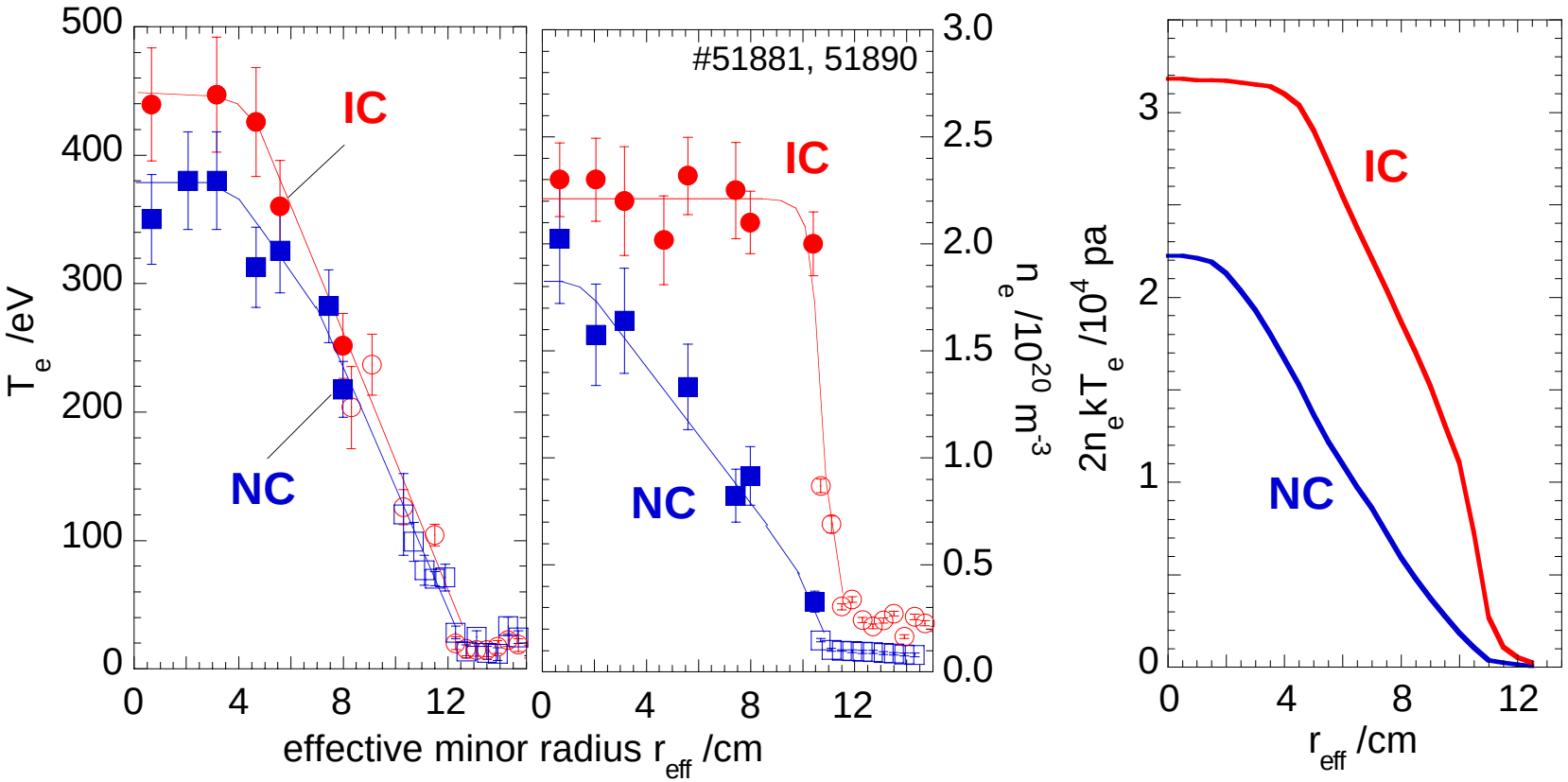


Improved confinement



Plasma performance at high density: core parameters

NC --> IC: broadening of n_e and pressure profiles



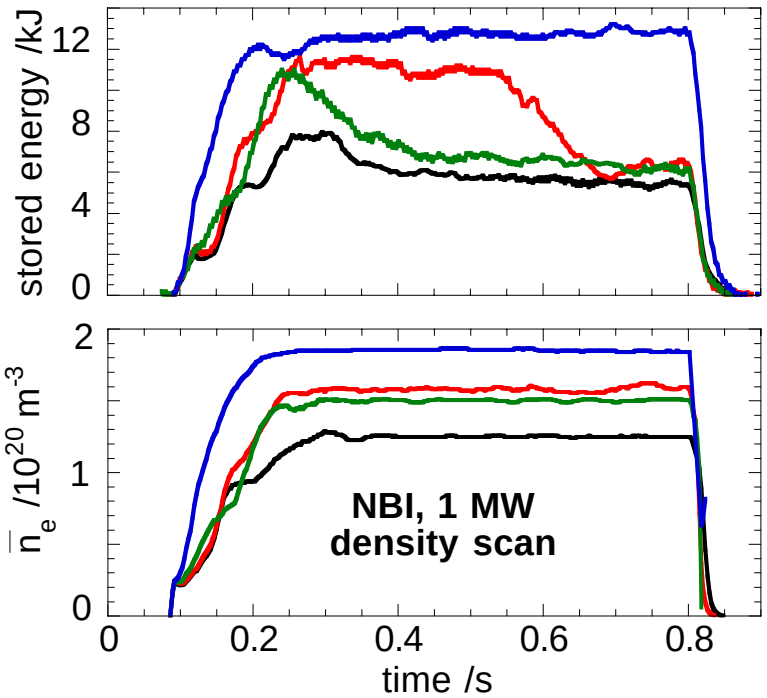
First SITAR code analysis of Al emission:

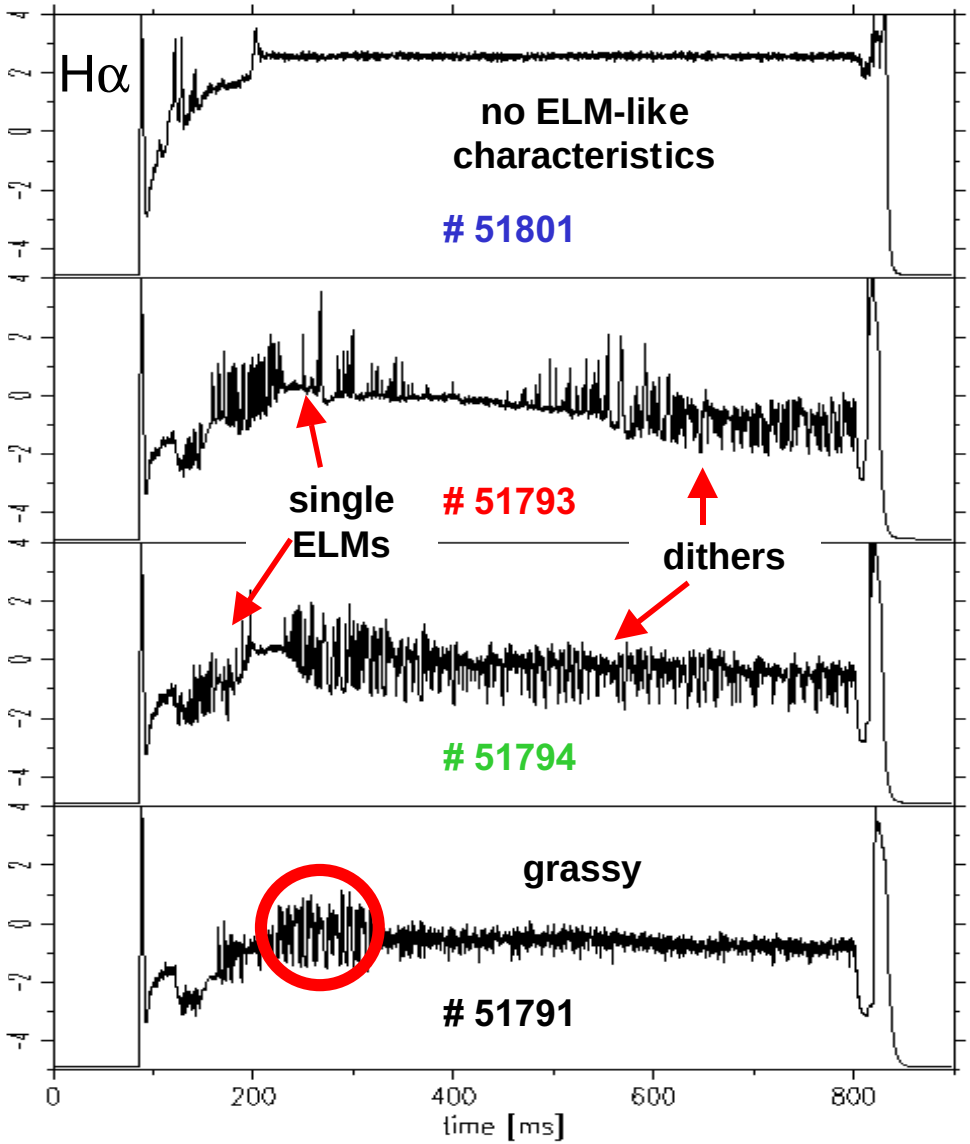
- nearly unchanged particle diffusivity,

- reduction of v_{in} by a factor of 4 - 5.

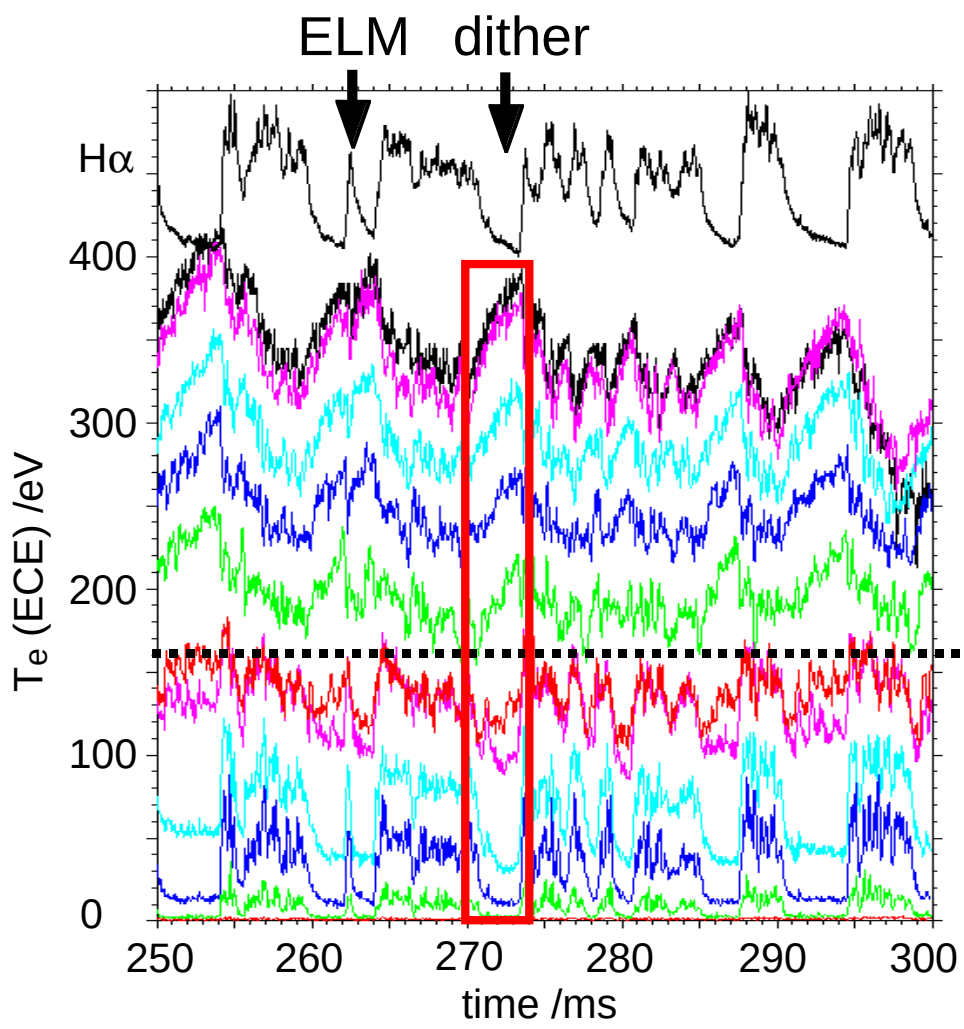
Plasma performance at high density: H-mode?

Hα traces:
H-mode like signatures during transition to IC





Plasma performance at high density: H-mode?

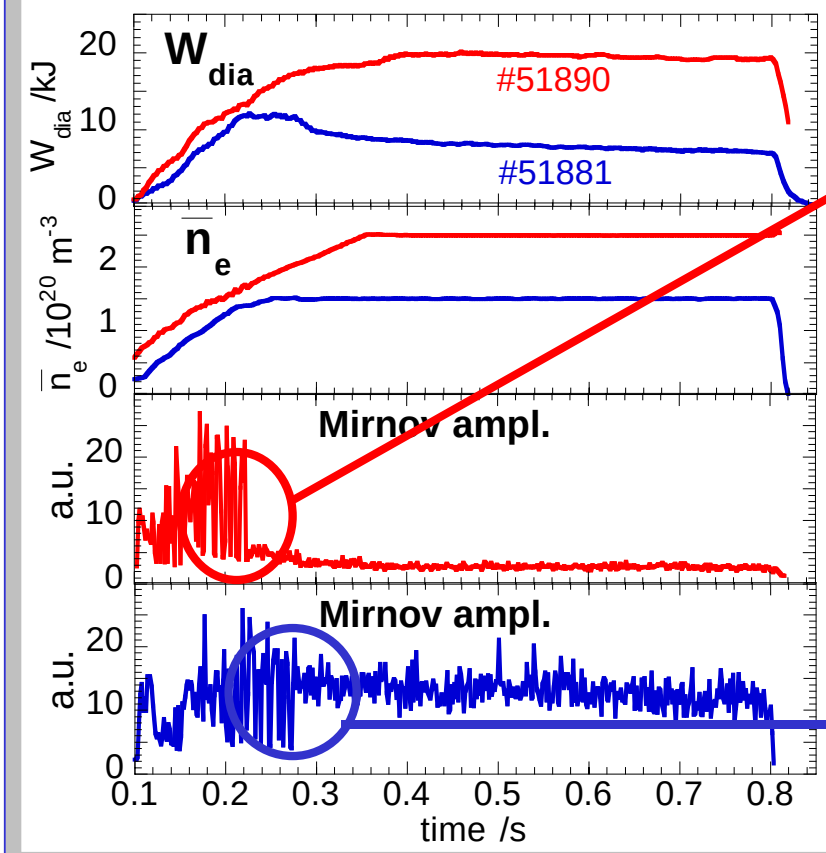


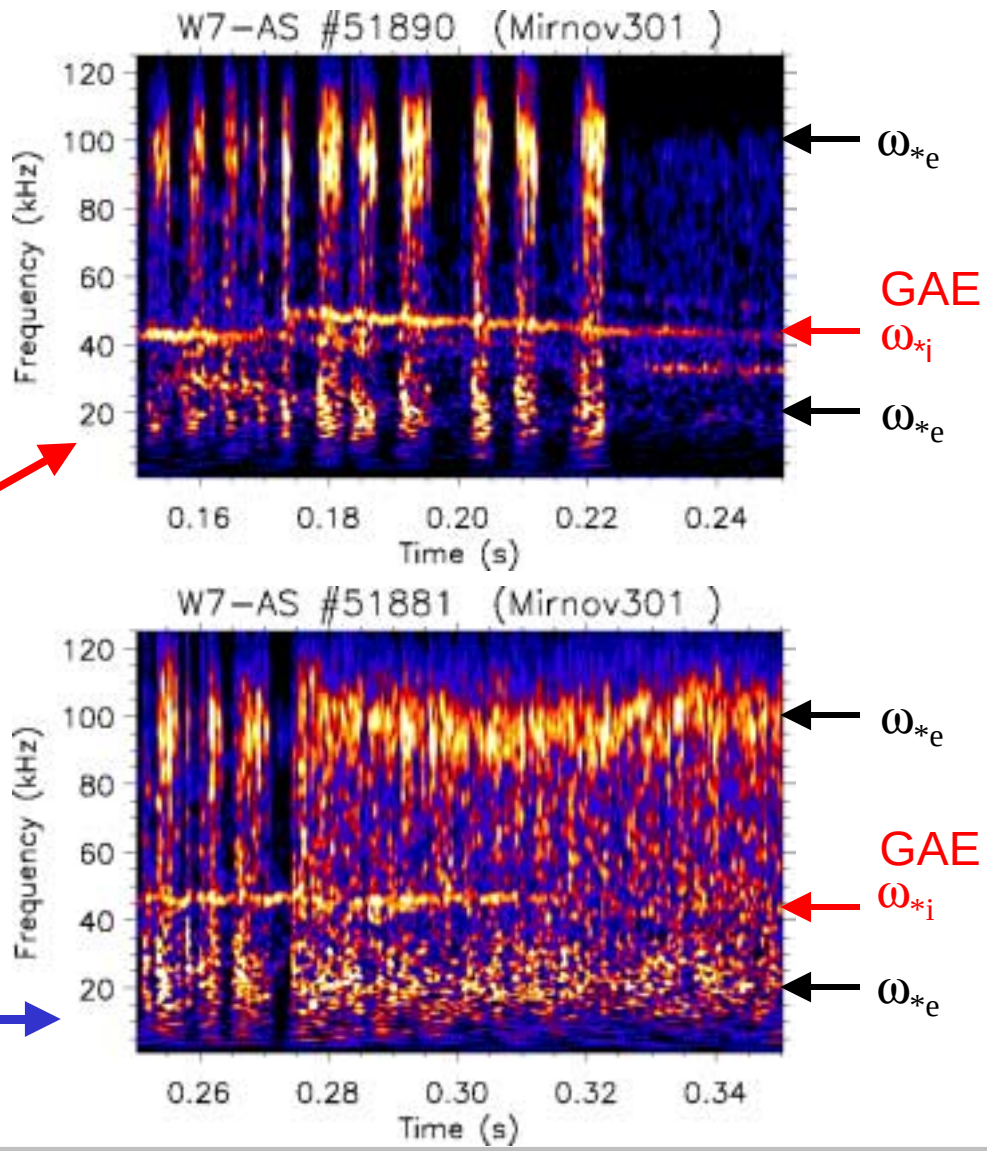
T_e (ECE) traces:
H-mode signatures during transition to IC

Pivot point

Plasma performance at high density: H-mode?

MIRNOV spectra:
H-mode signatures
during transition to IC

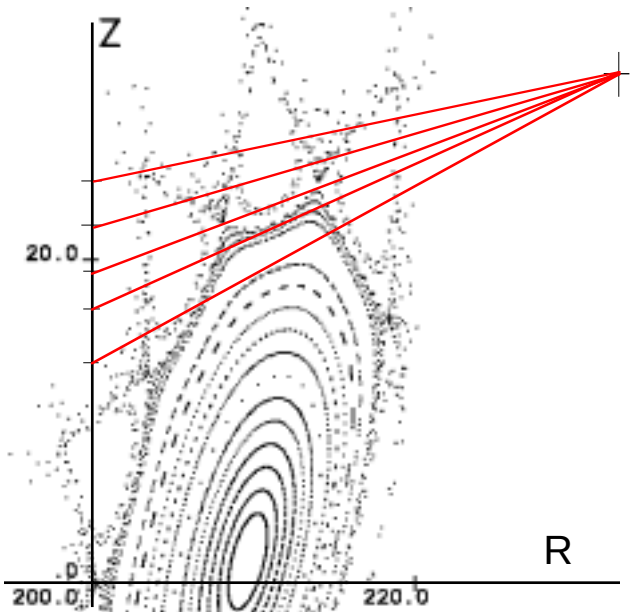


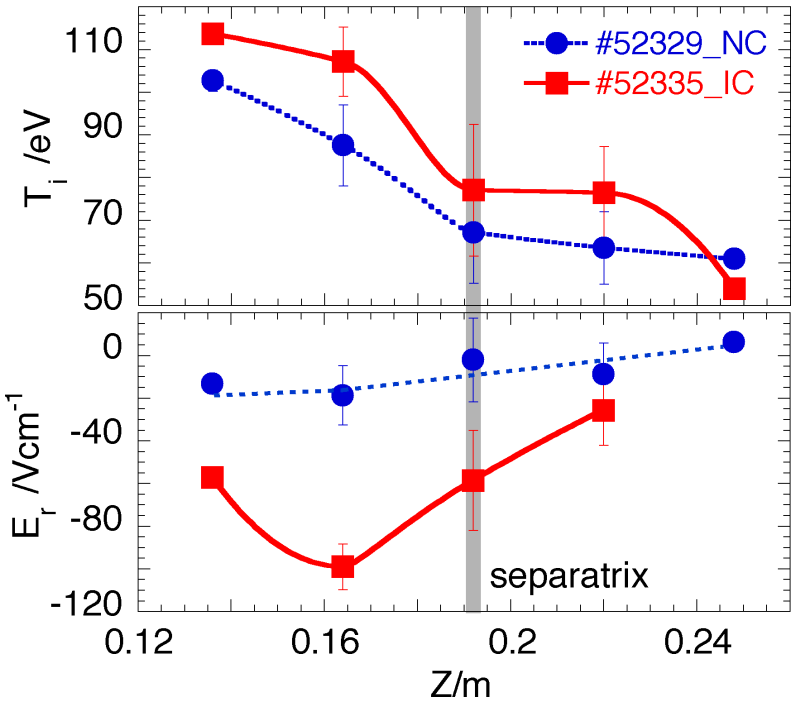


Plasma performance at high density: H-mode?

BIV spectroscopy:

- **radial E-field and spin-up develop,**
- **but less then in conventional H-mode.**





Summary of H-mode:

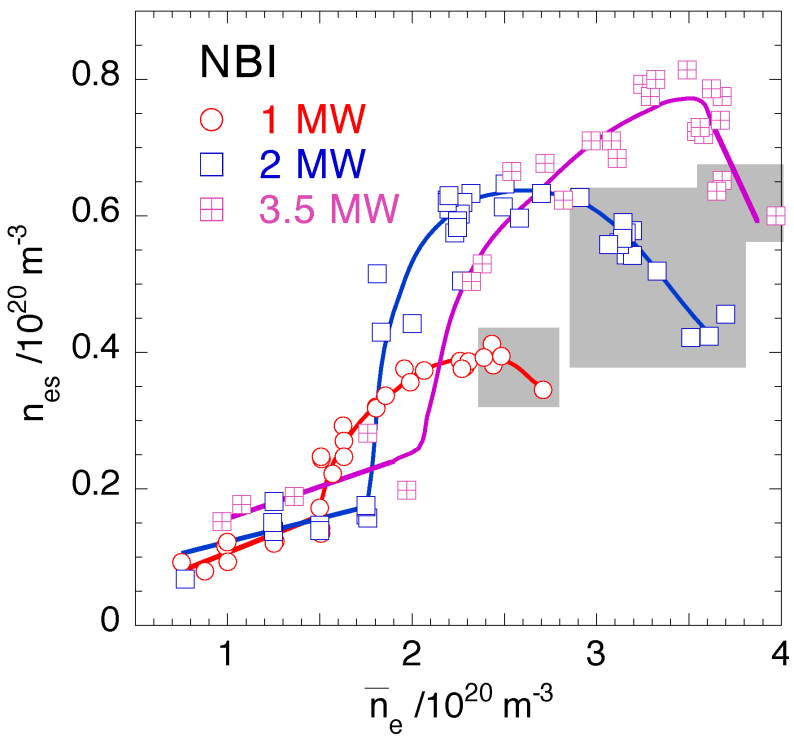
- **H-mode signatures during transition regimes,**
- **moderate E_r and poloidal spin-up,**
- **no accumulation problem in quiescent (IC) regime**

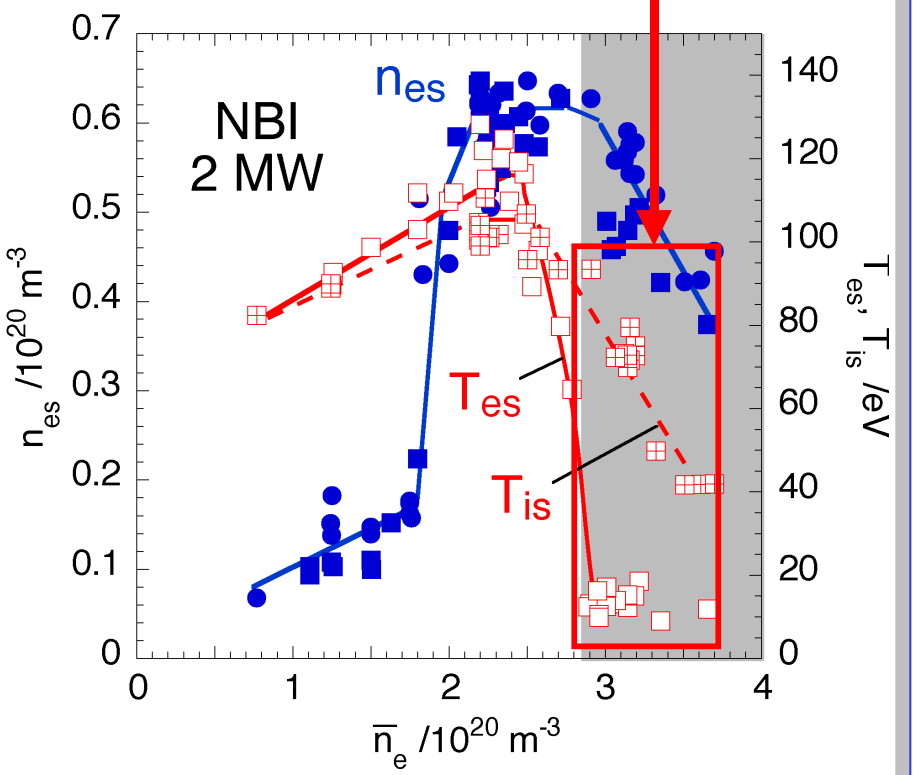
Plasma performance at high density: edge parameters

NC ---> IC---> detachment:

- **edge density n_{es} increases steeply**
- **drops at detachment**

- **edge temperatures T_{es}, T_{is} drop already prior to detachment,**
- **T_{is} >> T_{es} (different locations) ---> inhomogeneous T_{es}?**

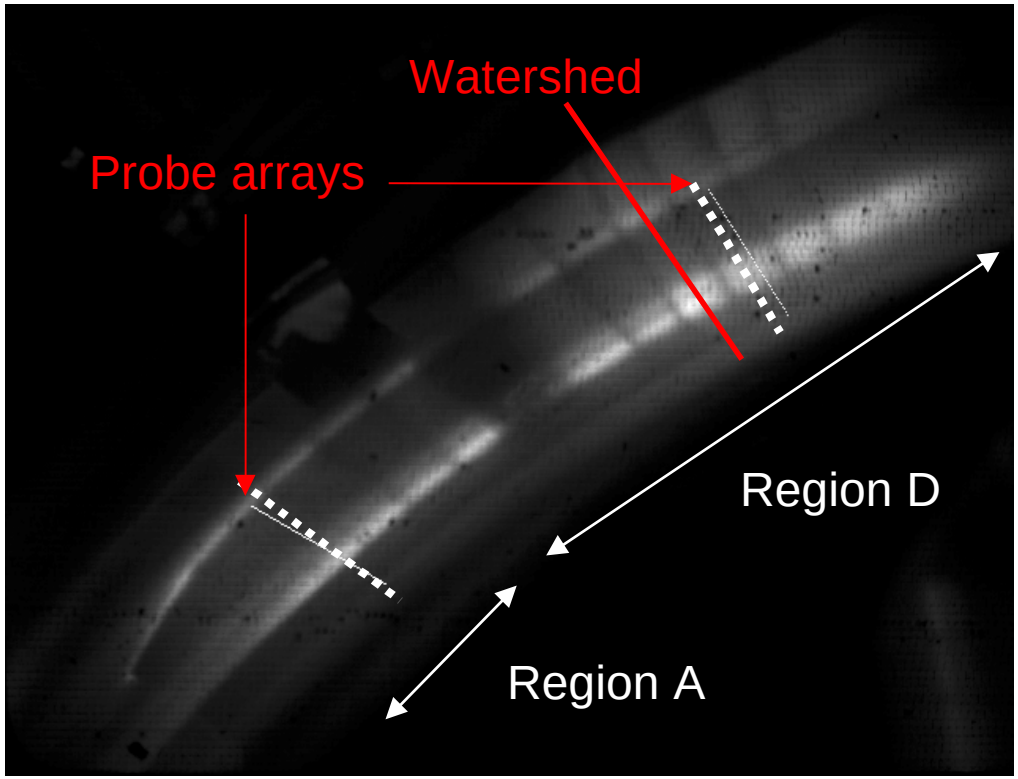




Divertor regimes

The plasma-target interaction concentrates mainly at helical stripes

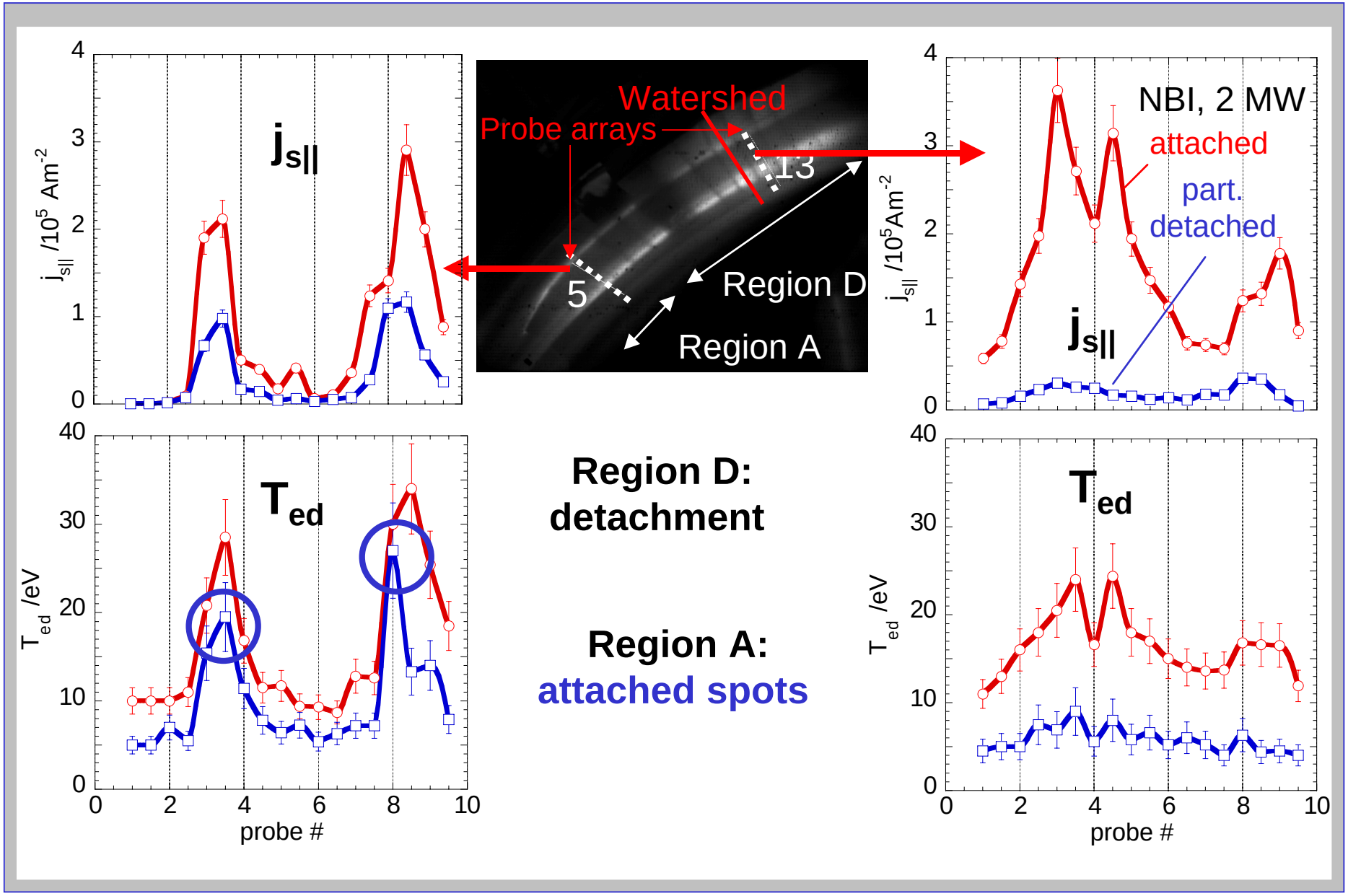
Hα traces



Region D:
rollover and detachment of energy and particle flux at high density

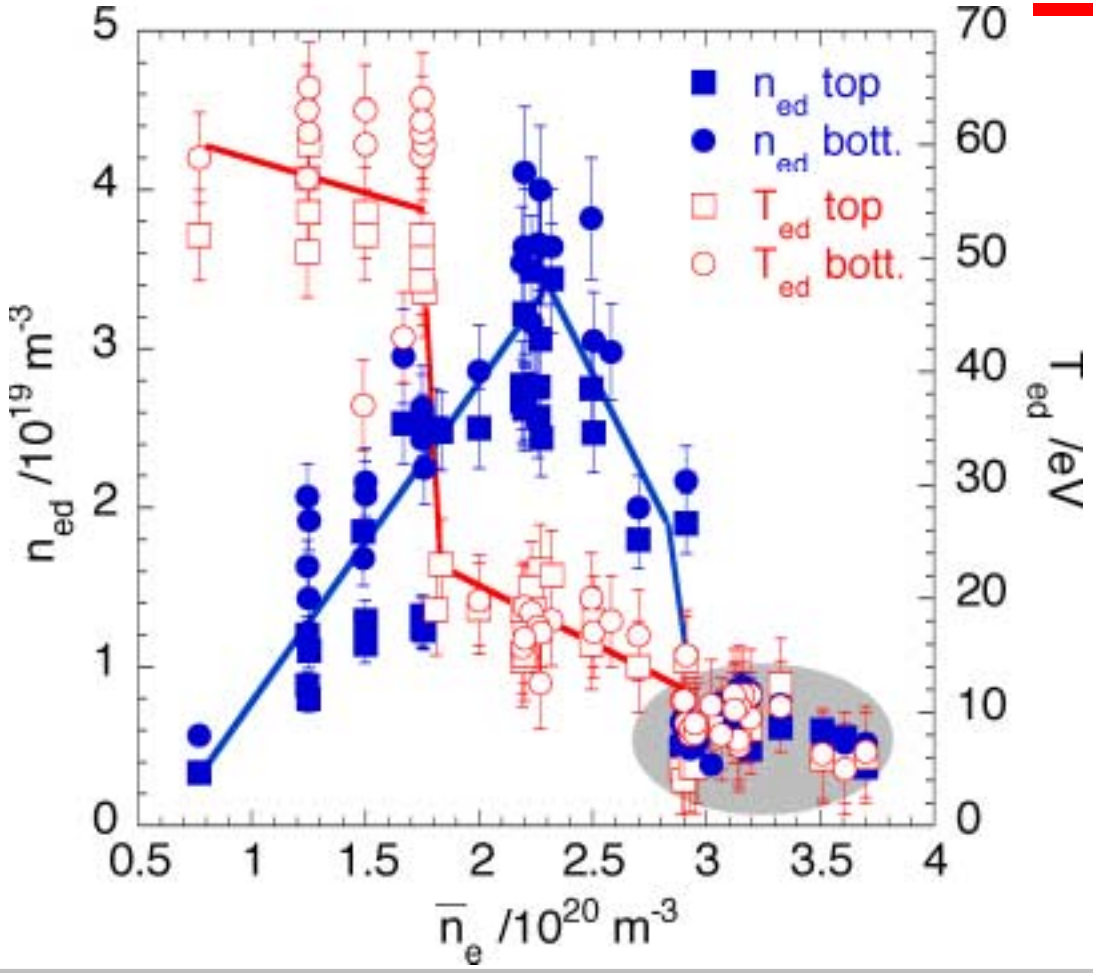
Region A:
attached spots even at highest density

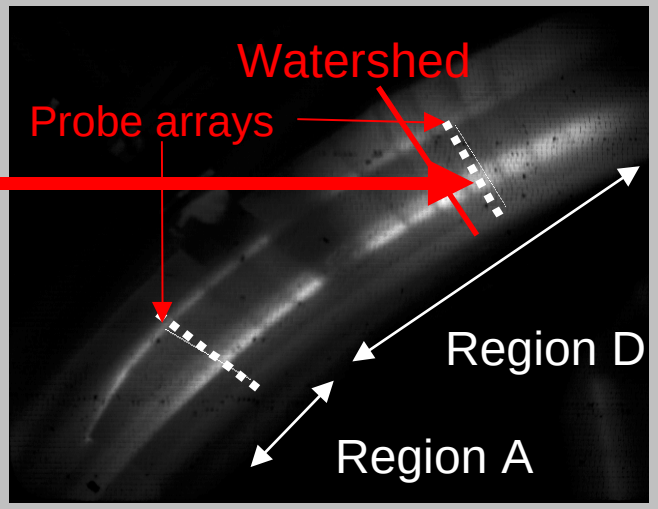
Divertor regimes: downstream parameters



Divertor regimes: downstream parameters

Peak densities and temperatures from probe array



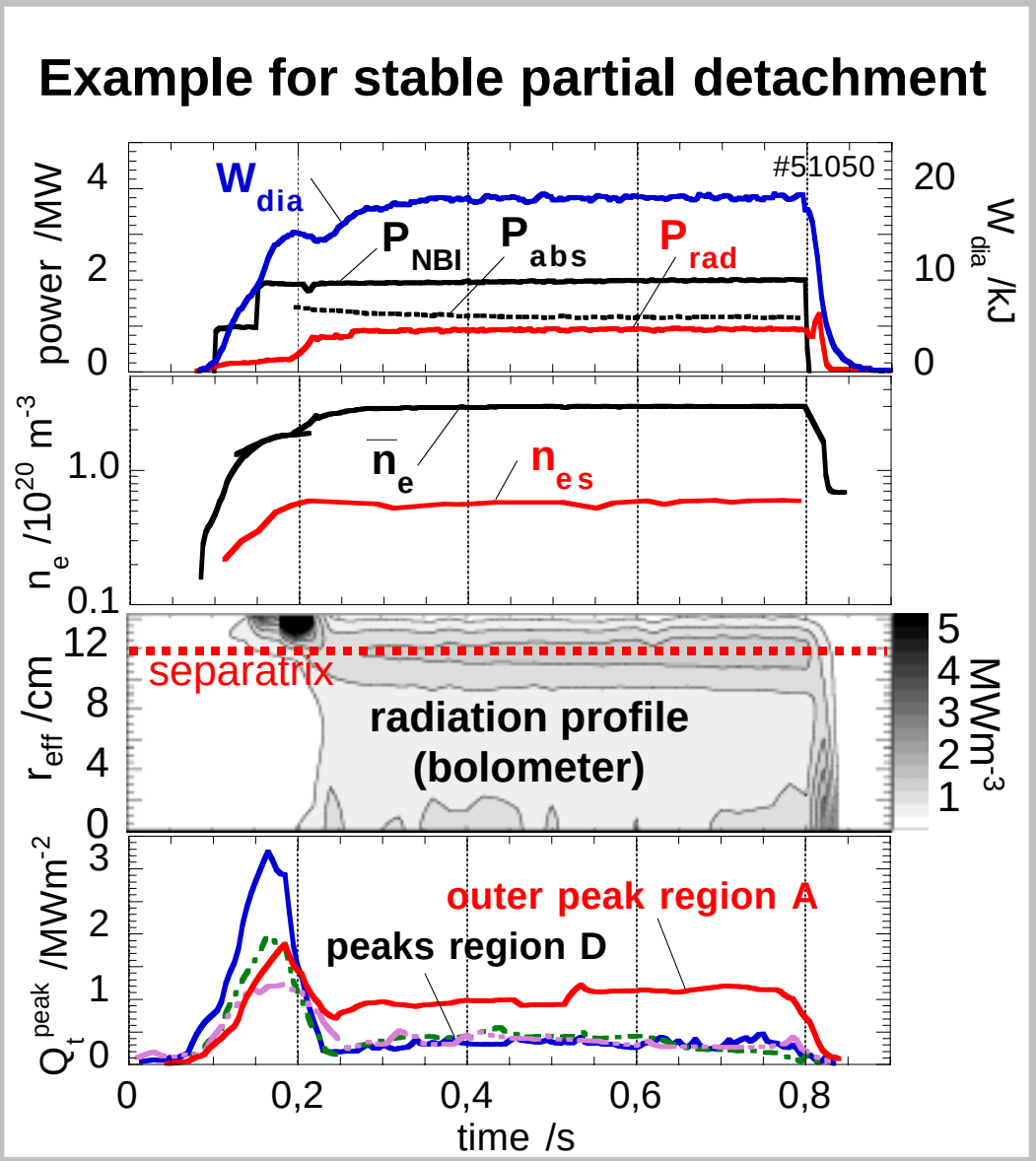


Region D:

-rollover up to detachment of n_{ed}, Γ_{pd} (confirmed by 2D H_α data)

- T_{ed} > 2 eV at detachment (from H_α/H_γ)

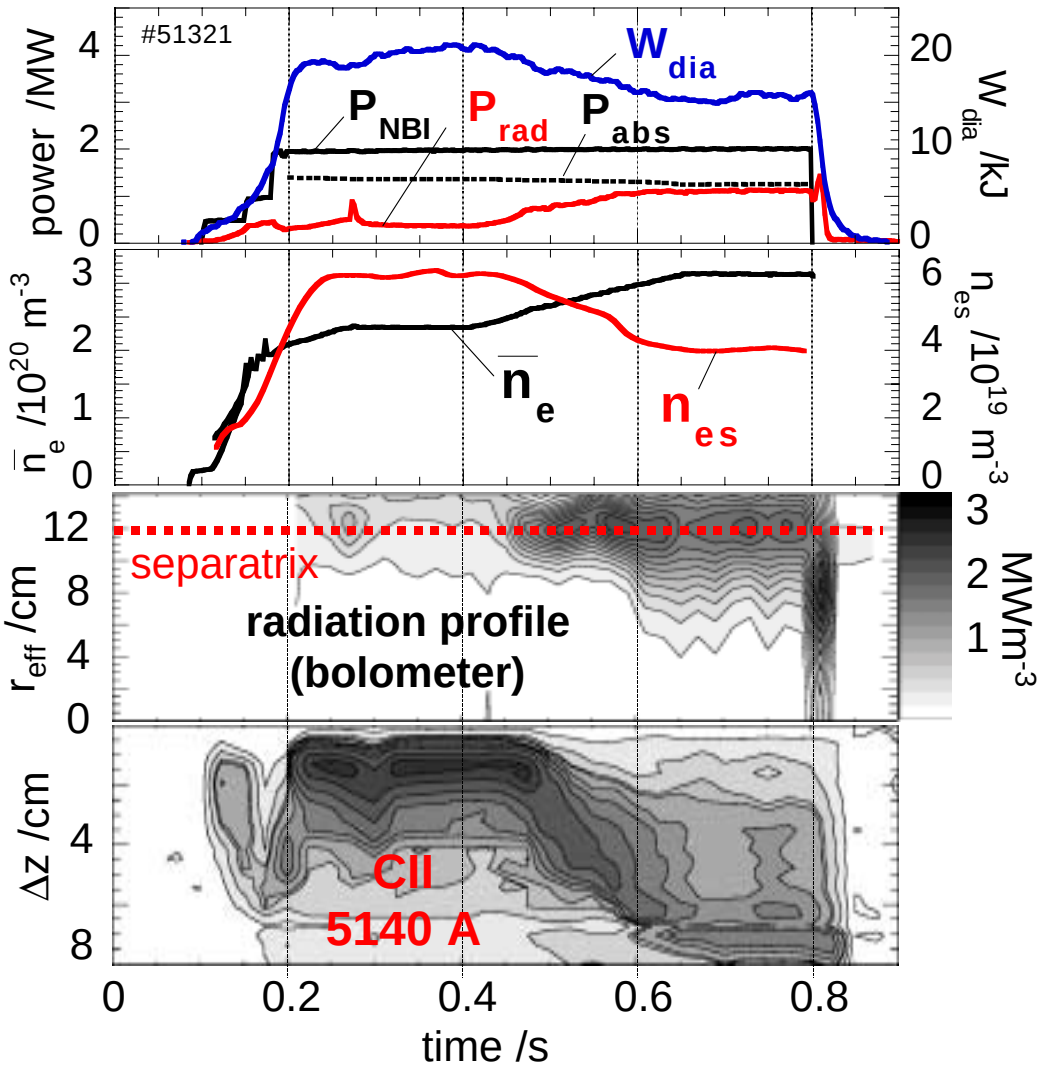
Divertor regimes: stable partial detachment



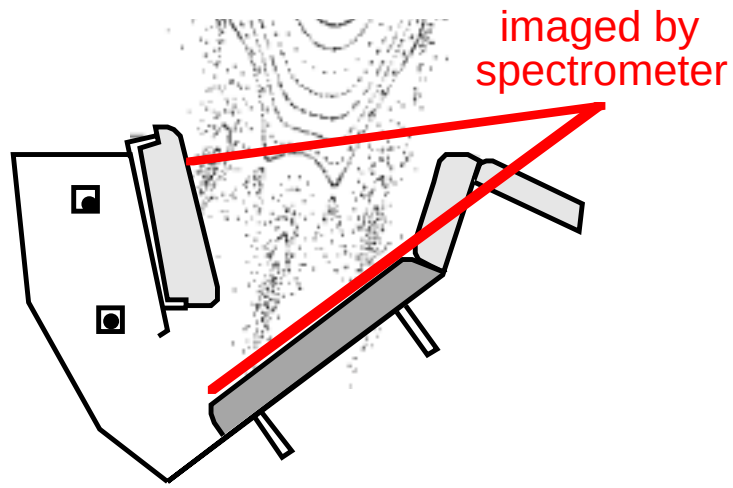
- $\bar{n}_e = 3\ 10^{20}\ m^{-3}$
- $T_e(0) = 400$ eV,
- $T_{es} = 20$ eV (?)
- radiated power fraction up to 80%
- radiation peaked at the separatrix position
- outer peak in region A attached,

Divertor regimes: controlled transition to part. detachment

Transition to ‚stronger' part. detachment



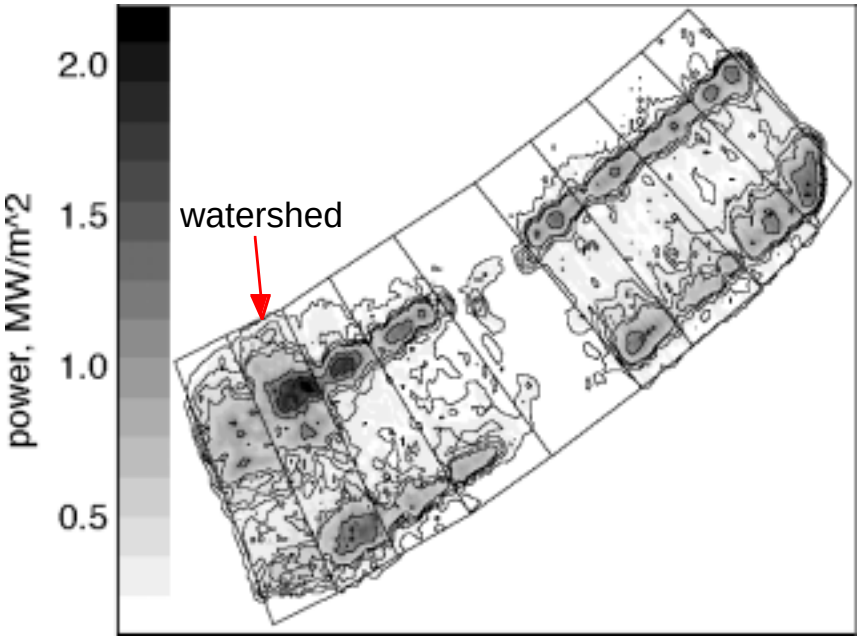
- radiated power fraction ≈ 85%,
- edge radiation dominated,
- T_{es} ≈ 15 eV, n_{es} drops,
- peak of C II radiation shifts in controlled way towards the x-points.



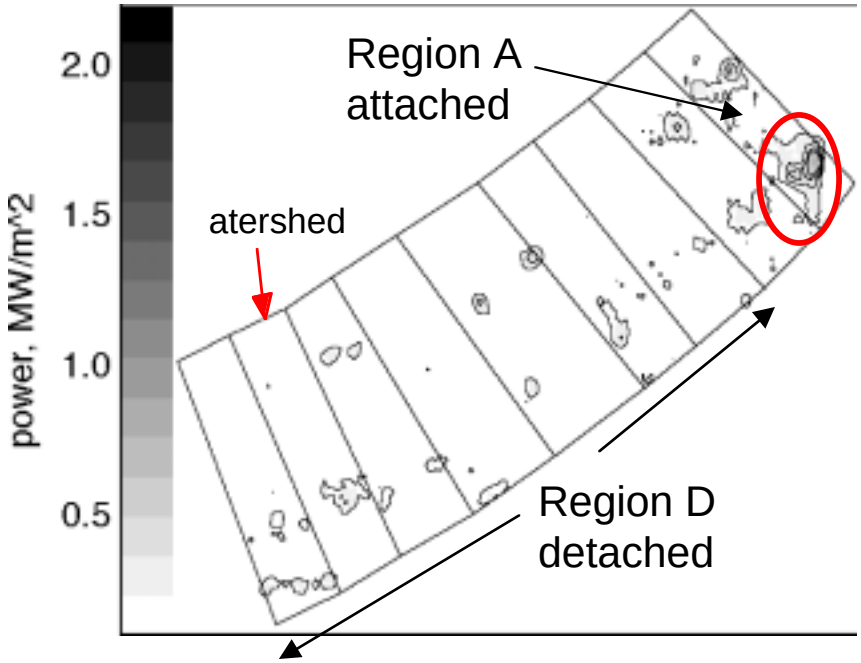
Divertor regimes: reduction of thermal load

Thermal load patterns on target, discharge #51321
(3D calculation from thermography)

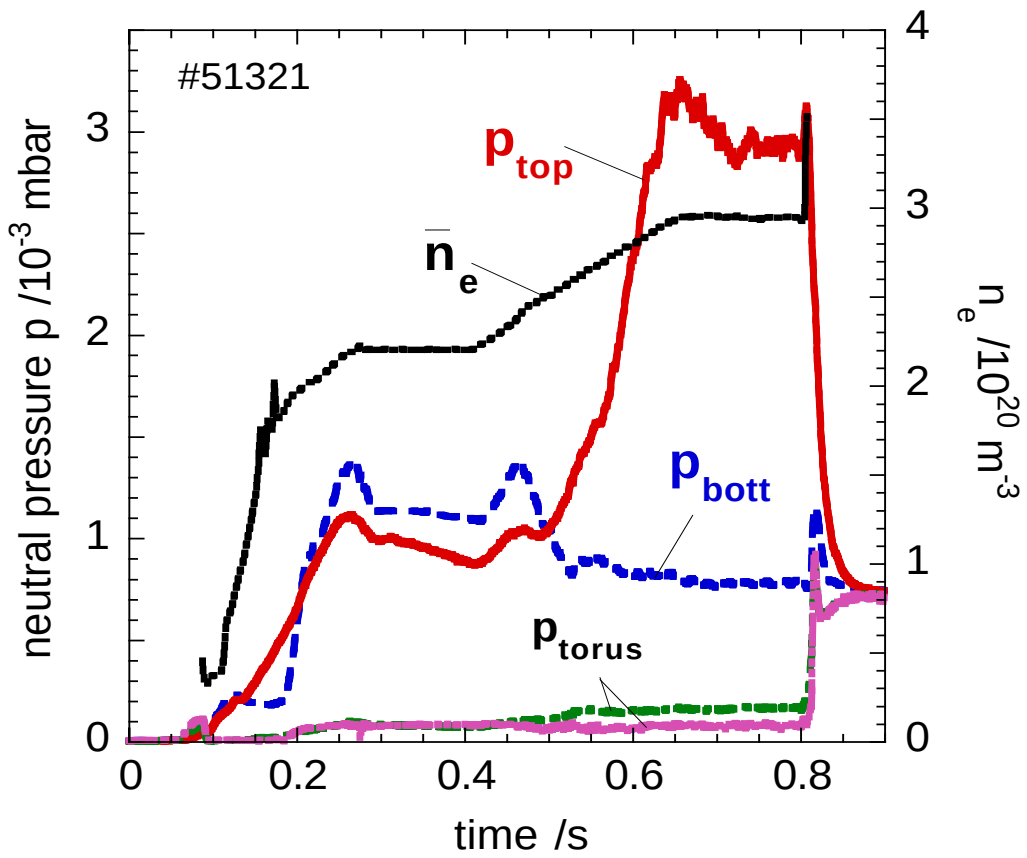
t = 0.35 s, attached



t = 0.65 s,partially detached

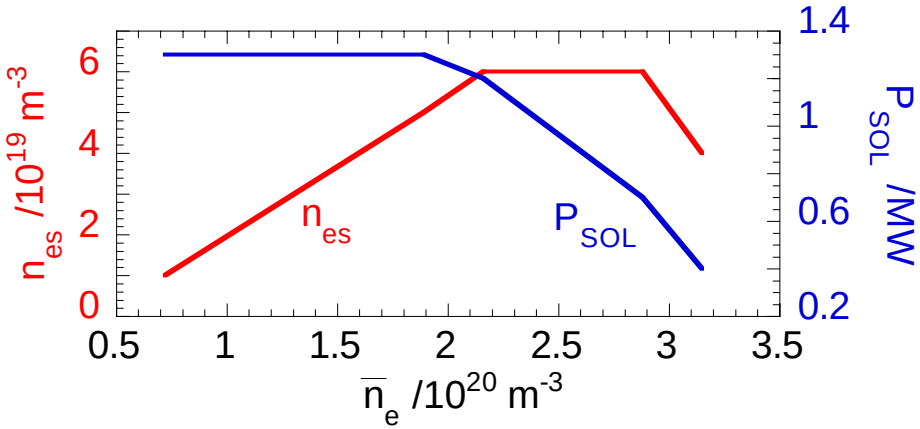


Divertor regimes: neutral pressures



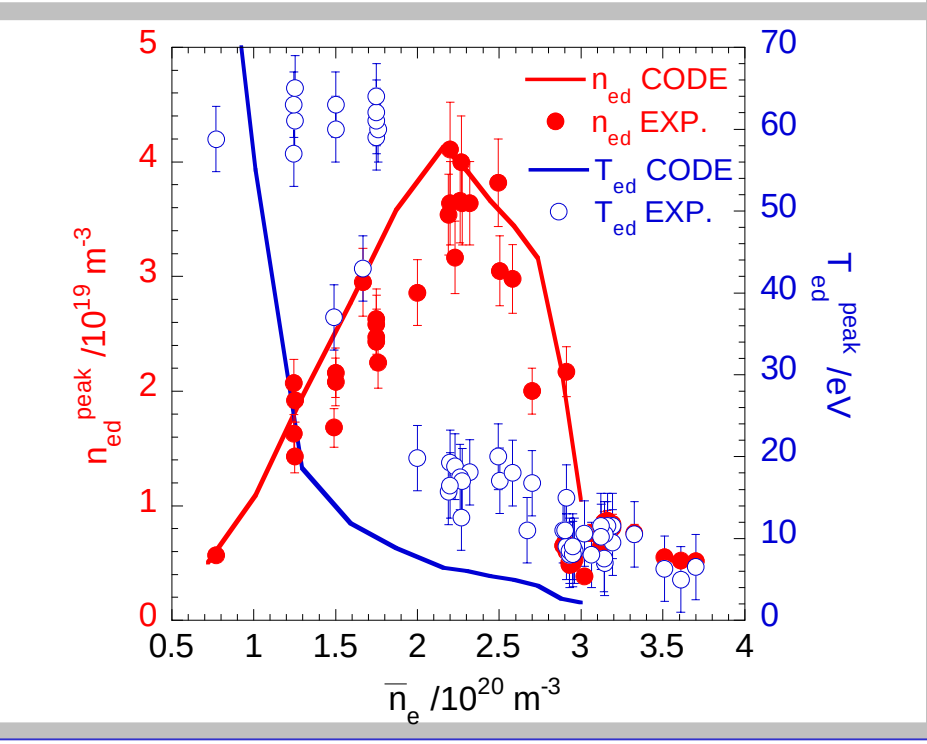
- steep increase of p_o in divertor subvolume during part. detachment,
- sufficient for pumping
- strong up/down asymmetry
- asymmetry inverts at low density,
- main chamber $p_o \approx 10^{-4}$ mbar

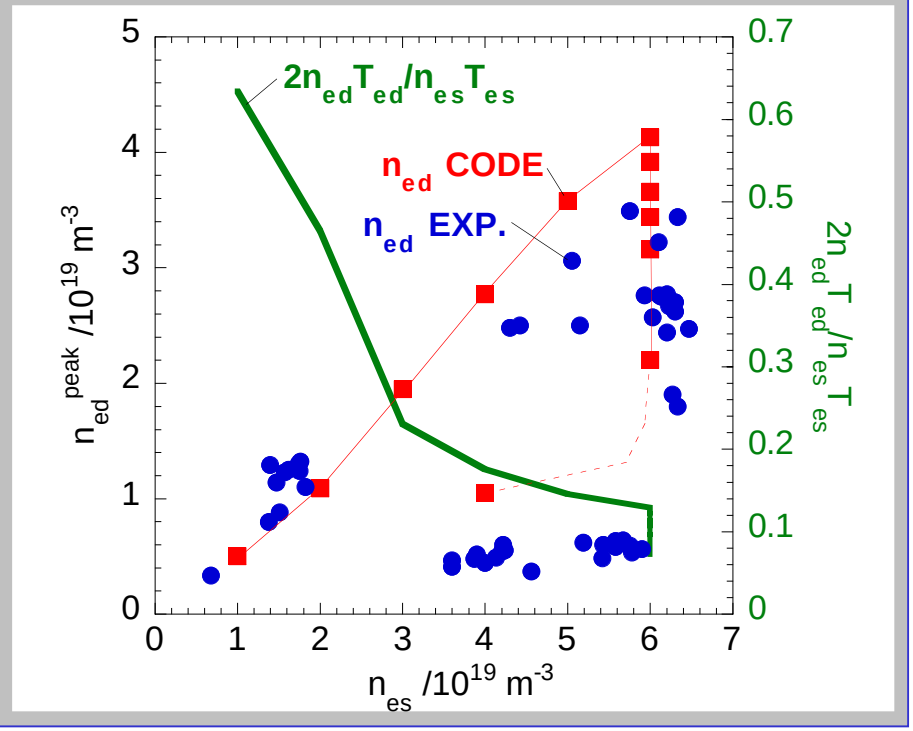
Divertor regimes: modelling of basic tendencies (Feng, Sardei)



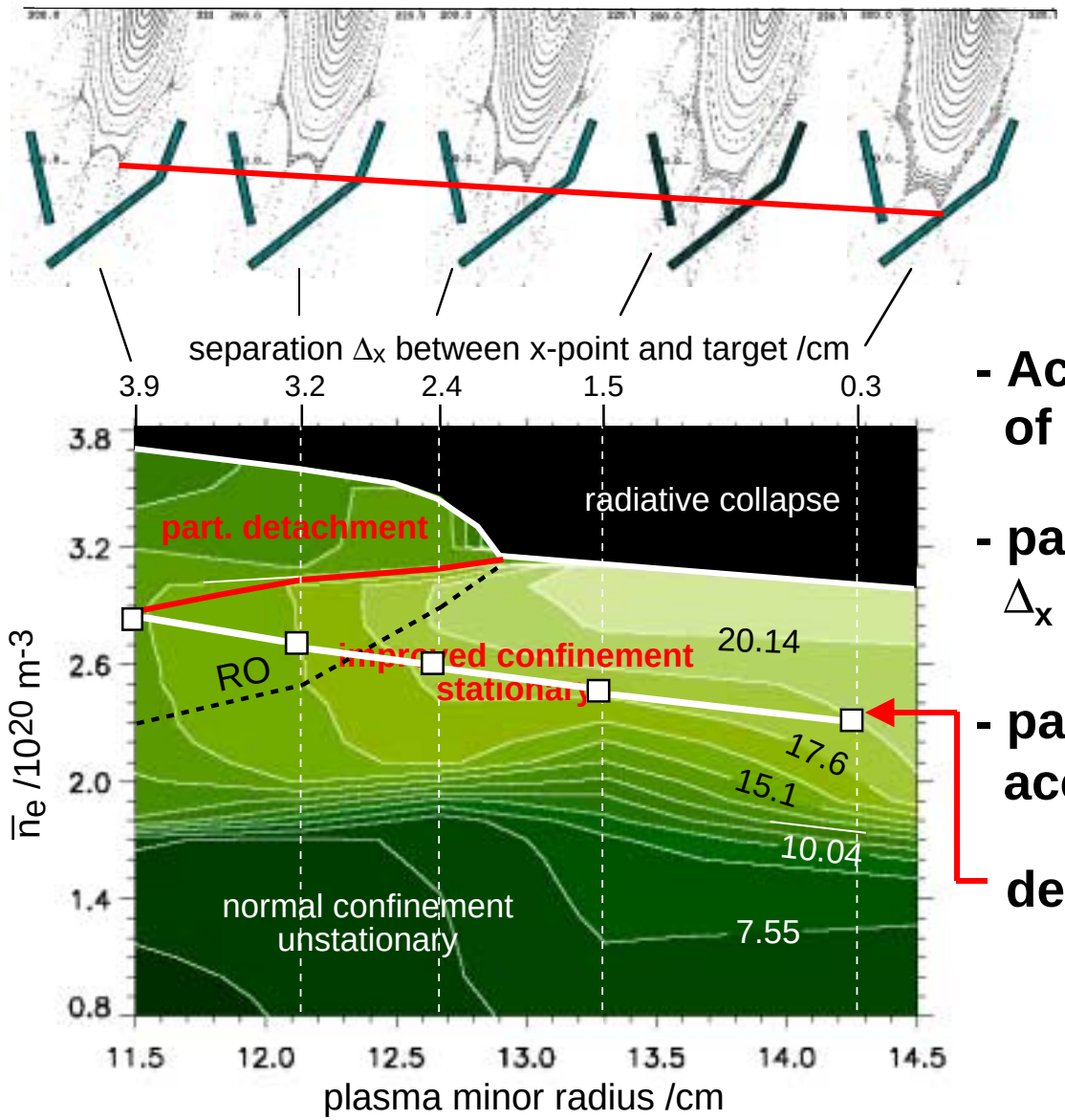
EMC3-EIRENE input parameters:

- P_{SOL} adjusted
- n_{es} adjusted
- χ = 3D = 0.5 m²/s
- carbon sputtering coef. = 3%





Operational ranges and density limit



Variation of a_{pl} and Δ_x by control coil currents

NBI, 2 MW:

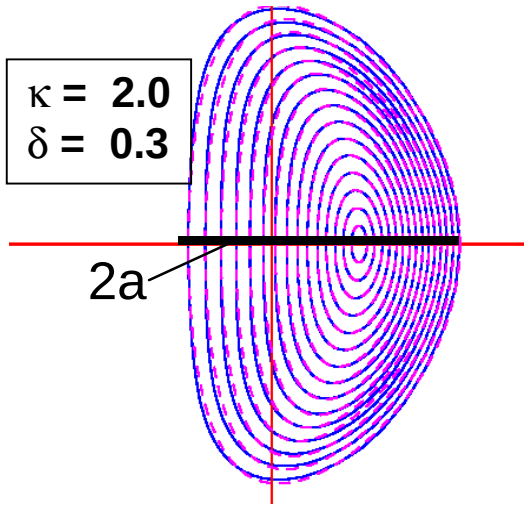
- **Access to IC independent of Δ_x,**
- **partial detachment at $\Delta_x \geq$ 2.4 cm**
- **partial detachment extends accessible density range**

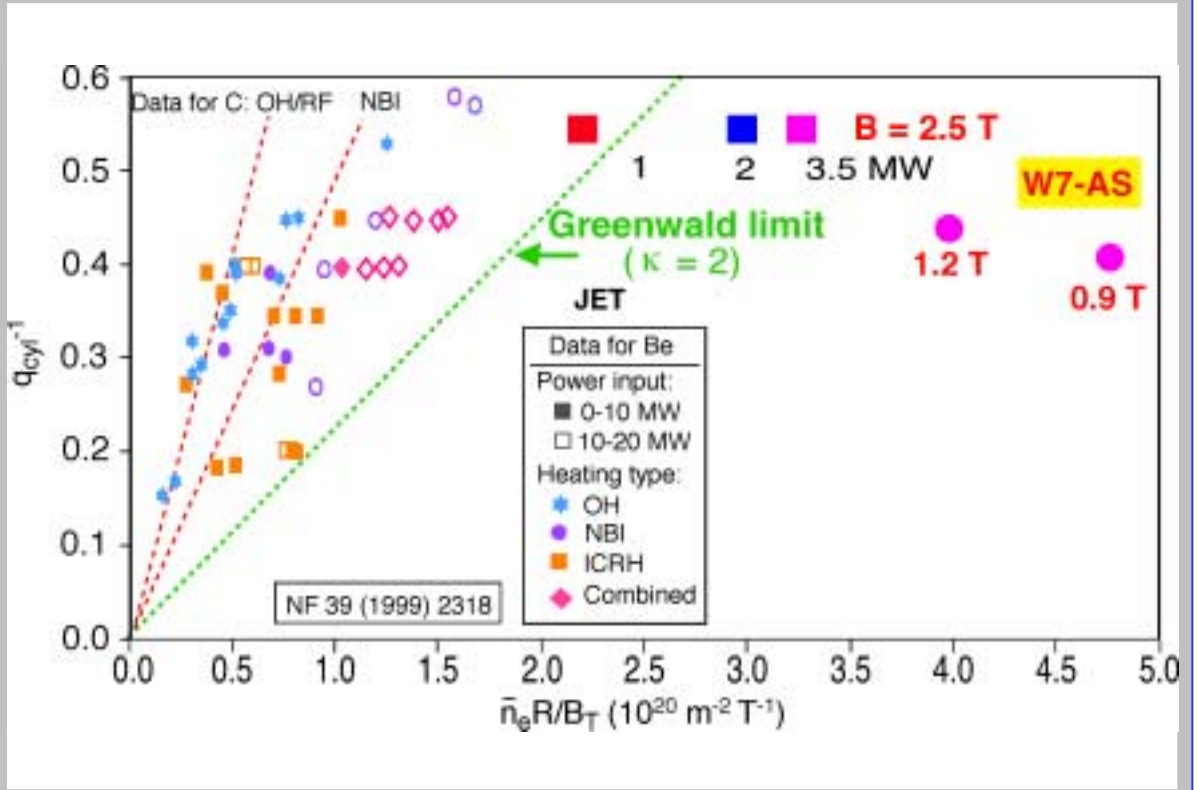
density limit SUDO et al.

$$n_s = 0.25\,(PB/Ra^2)^{1/2}$$

Operational ranges and density limit

toroidally averaged surfaces and fit by κ and δ





$$\frac{1}{q_c} = 2\frac{RI_{eq}}{5a^2B} / [1+\kappa^2(1+2\delta^2-1.2\delta^3)]$$

$$\bar{n}_G = \kappa \bar{J} = I_{eq}/\pi a^2$$

Summary

- Access to a new NBI, high-density regime (up to $\bar{n}_e \approx 4x10^{20}$ m^{-3}) with high τ_E and low τ_p and τ_{imp}
- The new regime is characterized by flat density profiles with steep gradients at the edge,
- Full density control already without Ti-gettering,
- Quasi-steady state operation also including partial detachment,
- Edge-dominated radiation, radiated power fractions are low to moderate in attached and high (up to 90%) in detached regimes
- Detachment is partial: it does not extend over the full target area, and the particle and energy fluxes stay finite (T_{ed} > 2 eV)
- Improved confinement in all separatrix-bounded configurations,
- Stable part. detachment restricts to configurations with larger distance between x-points and targets (divertor configurations).